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SUBJECTIVE RESPONSE TO SYNTHESIZED FLIGHT NOISE SIGNATURES OF SEVERAL TYPES OF V/STOL AIRCRAFT

by Ernest G. Hinterkeuser and Harry Sternfeld, Jr.

Prepared by
THE BOEING COMPANY
Philadelphia, Pa.
for Langley Research Center

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By Ernest G. Hinterkeuser
and Harry Sternfeld, Jr.
The Boeing Company, Vertol Division

SUMMARY

The acoustical signatures of various types of V/STOL aircraft sized for 60 passengers and a 500 mile range were analytically predicted, and tape recordings synthesizing these sounds prepared. Test subjects listened to these sounds and compared their annoyance with that of a jet airplane. Perceived noise levels were calculated, and the levels which produced equal annoyance to the jet were determined. Each aircraft was analyzed to determine the distance it must maintain from observers in order not to exceed the annoyance of the jet airplane during terminal and flight operations. A second analysis was made to identify the noise reduction required for each aircraft in order to operate at specified distances at a specified level of annoyance. The aircraft studied were helicopters, fan lift, jet lift, and tilt wing VTOL and a turbofan STOL.

The results of the tests and analyses indicate that several V/STOL aircraft configurations exhibit subjectively better acoustical characteristics than others depending on flight configuration and inherent differences in propulsion systems. Quantitative guidelines for the evaluation of public reaction to the noise of these configurations are given in Figures 13 and 16. Component noise reduction requirements are summarized in Figure 17. The feasibility of synthesizing subjectively acceptable aircraft noises and the usefulness of paired comparison testing have been demonstrated.

INTRODUCTION

The purpose of this study was to evaluate subjective response to the far field noise characteristics of several types of V/STOL aircraft sized to carry 60 passengers over a 500 mile range. Since several different types of noise sources are involved, one of the expected results of such studies is the identification of particular components of the aircraft which may require modification for noise reduction during terminal and/or cruise operating conditions.

The problem of aircraft noise and its effect on the public is one which has been of increasing concern. The development of the jet airplane and its ever increasing size and power, combined with the rapid growth in air traffic density, have tended to focus attention on the need for criteria which could be used for regulatory purposes or to evaluate the acceptability of new and proposed aircraft.

The most widely accepted answer to this need to date has been the development of perceived noise level (PNL) (references 1 and 2). The PNdb regulations currently in use, however, consider only the spectral content and level of the acoustical signature and do not consider factors such as time duration and presence of pure tone components.

While the development of a noise criteria index which will apply uniformly to all aircraft sounds (or, even better, to all sounds) should be an ultimate objective of researchers in psycho-acoustics, this goal is not clearly attained by the present PNdb calculation, nor by any of the proposed modifications, in that universality of application is yet to be demonstrated. This program, which has as its objective an assessment of the noise produced by various aircraft configurations, seeks to determine that PNdb level measured outdoors which, for a given configuration, will cause the same public reaction from people indoors as a jet airplane producing 112 PNdb outdoors. This will be referred to as the comparative perceived noise level of the aircraft. The method of arriving at the comparative perceived noise level is illustrated in Figure 1.

The method of paired comparisons is employed because it tends to cancel out many physical and psychological differences between subjects which might be present in an absolute judgment test.

It is apparent that an investigation such as this one can only be successfully achieved by a blending of the skills involved in both acoustics and psychology. This program was greatly enhanced by the guidance of its two consultants, Dr. Roy Hackman, Professor of Psychology, Temple University, and Dr. Karl Kryter, Stanford Research Institute. Dr. Hackman advised on survey form design, statistical handling and validation

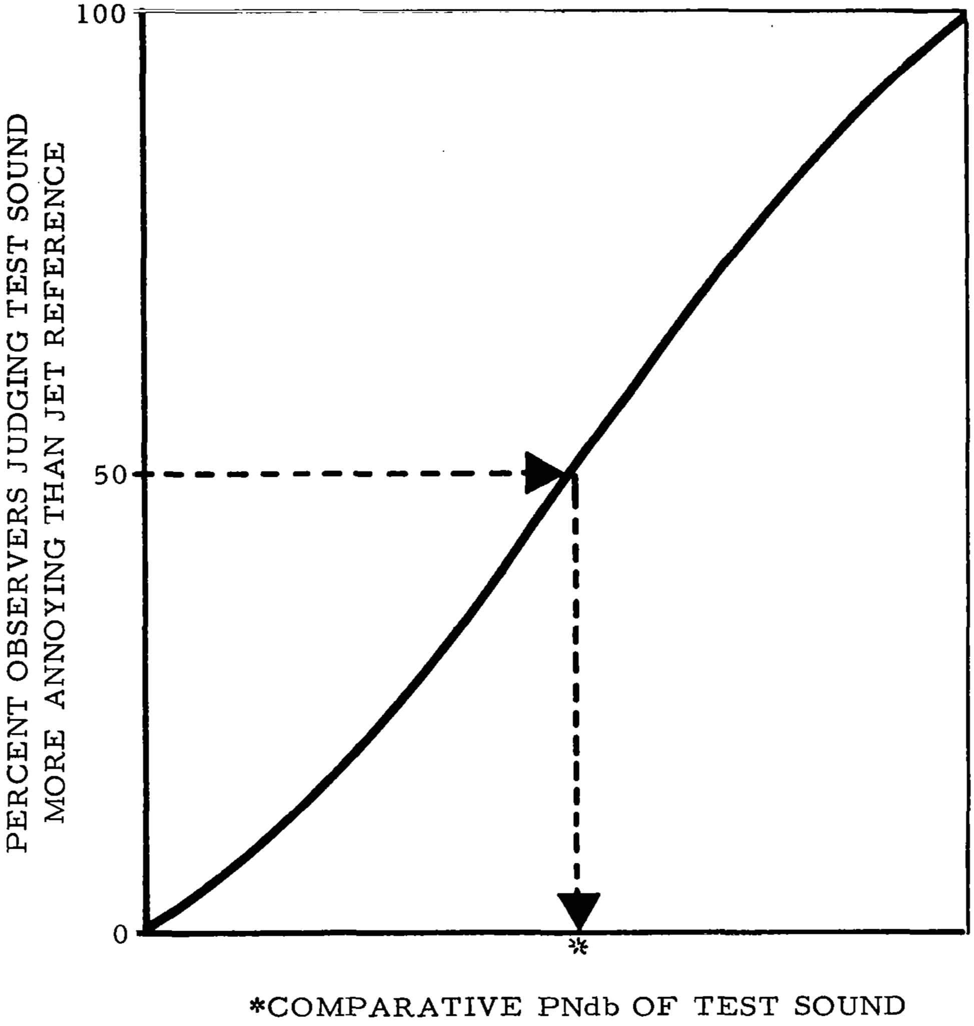


Figure 1. General Method of Obtaining Comparative Perceived Noise Level.

of the data, and conducted the test sessions. Dr. Kryter not only provided continuity with previous and current work regarding perceived noise level but also consulted on preparation of test samples and interpretation of the test results. The cooperation of the staff of PMC Colleges, Chester, Pennsylvania, is gratefully acknowledged for providing a test site and securing test subjects. All data reduction, test result compilation, and calculations were performed by Miss Marna H. Cupp.

PRELIMINARY ANALYSIS

The basis for the present research project was a study of VTOL and STOL short-haul transports conducted for the NASA Ames Research Center (references 3 and 4). In that program, VTOL and STOL aircraft were analyzed in order to determine those most suitable for commercial short-haul operation and the research required to bring them to full operational status. The study covered aircraft design, operational techniques, noise and public acceptance, acquisition cost, direct operating cost, technical risk, and research requirements.

The summary of reference 3 states that the lift fan VTOL, jet lift VTOL, tilt wing VTOL, and turbofan STOL are the most promising concepts. A rigid single rotor composite aircraft and a tandem rotor helicopter were also evaluated to provide more complete coverage of the disc loading spectrum.

Ground rules covering aircraft design included a 500 statute mile nonstop range, contingency ratings for prime or auxiliary engines, specified flying qualities, and 60 passenger payload capabilities. Appendix A describes the various aircraft and provides the predicted acoustical spectra for each.

SIMULATION

There were three basic sources available for the sounds required to simulate the aircraft under study: (a) tape recordings of aircraft of the same general configuration; (b) tape recordings of specific components of a given configuration such as a rotor, propeller, etc.; (c) electronically synthesized noise. Whenever possible, source (a) was employed due to the overall simplicity and because this method is most realistic.

When a single tape of the configuration was not available, sources (b) and (c), generally in combination, were used.

To synthesize aircraft sounds, detailed spectrum content, amplitude-time history, directivity index, and Doppler shift analyses were carried out to properly account for most of the subjective aural effects of an aircraft sound. If the source was a complete tape (source a) the procedure outlined in Figure 2 was followed. A description of each of the elements in Figure 2 follows.

Frequency shift. - When it was required to change all the frequencies in the signature proportionally, this was accomplished by re-recording the original tape (a) on a second recorder equipped with a variable tape speed control. Changing the tape speed resulted in an effective change in frequency content due to the relationship of the recorded wavelength to the rate at which the tape traverses the recording gap.

Spectrum shaping. - In order to alter the spectrum shape of the available taped sound to match the analytical prediction of the new aircraft, the signal was fed through a set of 1/3 octave band filters, each with independent attenuation control (c), which were pre-adjusted to produce the desired changes.

Amplitude-time. - Variation in sound pressure level with time is a function of the aircraft velocity, distance from the observer, and direction with respect to the observer. Since it was highly improbable that the available sound tape would display the desired rate of build up and decline of the signals, this was compensated for by providing a potentiometer and a graphic display of the output signal (d). By manual adjustment, the signal could then be built up or diminished in order to provide the desired time history for recording on the final master tape (e).

When the sounds were to be synthesized from components and electronic sounds, the procedure became more complex and is illustrated in Figure 3.

Taped components. - Taped components (a) were frequency shifted (b) and reshaped (c) in a manner similar to that previously described.

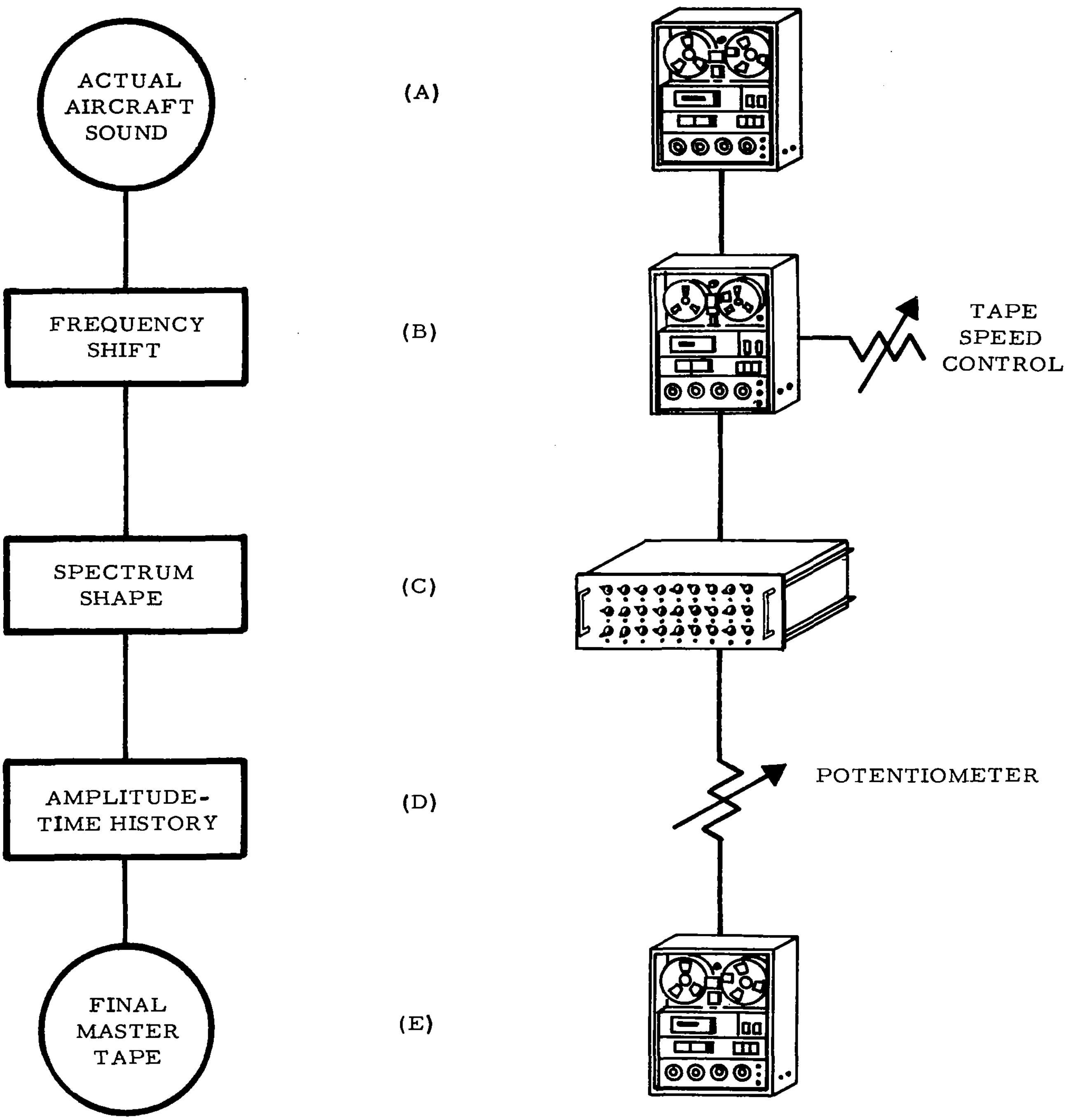


Figure 2. Synthesis of Aircraft Sound From Tape Recording.

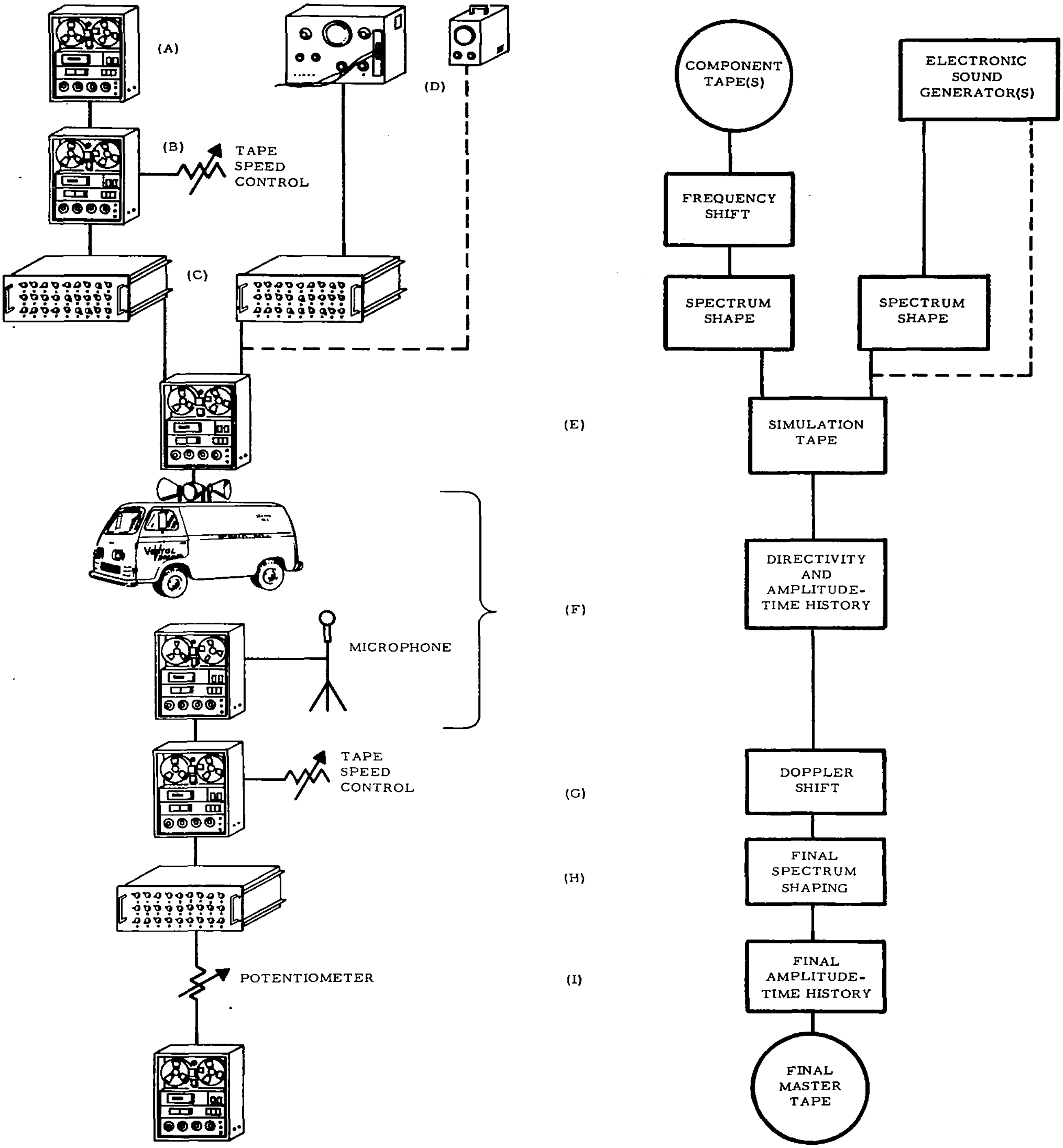


Figure 3. Synthesis of Aircraft Sound from Component Tapes and Electronic Instruments.

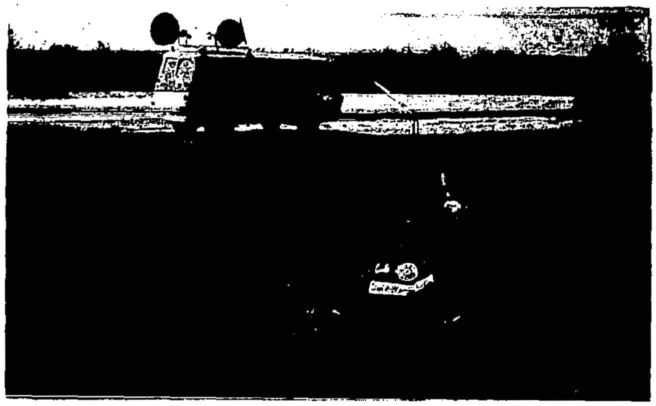
Electronic synthesis (d). - Broad band sounds were produced by random or white noise generators and were then filtered and shaped as required. Pure tones were generated by suitable oscillators.

Simulation tape (e). - Each separate component was then recorded on a single channel of a multichannel tape recorder for subsequent combining.

Directivity and amplitude-time history. - Since the sounds produced did not contain the qualities imparted by motion of the source (directivity, time variation or Doppler shift), these had to be introduced artificially. The first two of these effects were combined by the following procedure. The various synthesized sounds were combined on three tracks of a magnetic tape in proper proportion to produce the forward directed spectrum, the side directed spectrum and the aft directed spectrum. The output of each track was connected to a separate amplifier-speaker combination, mounted on a vehicle, and driven past a stationary microphone-recorder system (Figure 3f and Figure 4) approximately 75 feet away (see top of Figure 4). The distance was determined by vehicle and ambient noise levels. The result was a gradual build-up of sound with time as each component of noise would predominate: first the source with the approach noise, then the side directed noise, and then, on the fade-away portion of the sound, the aft directed noise. These tests were conducted out of doors permitting believable sound signatures to be recorded since the turbulence present in the atmosphere, even over short distances, provided realistic fluctuations in noise amplitudes.

To check the accuracy of the simulation against the results of the calculated frequency content of this sound, an analysis of the recorded noise was made after every few passes of the vehicle in the field. Figure 5 shows the equipment used to obtain octave-band frequency analysis of the simulated fly-by as a function of time.

An actual aircraft sound amplitude-time history is illustrated in Figure 6. Part b of the figure shows a first approximation to this sound using a shaped broad band random noise generated electronically whose amplitude as a function of time was controlled by a potentiometer on the random noise generator (volume control). It can be seen that the natural random amplitude fluctuations due to unsteady atmospheric effects are absent. The sound does not seem real to a listener even if



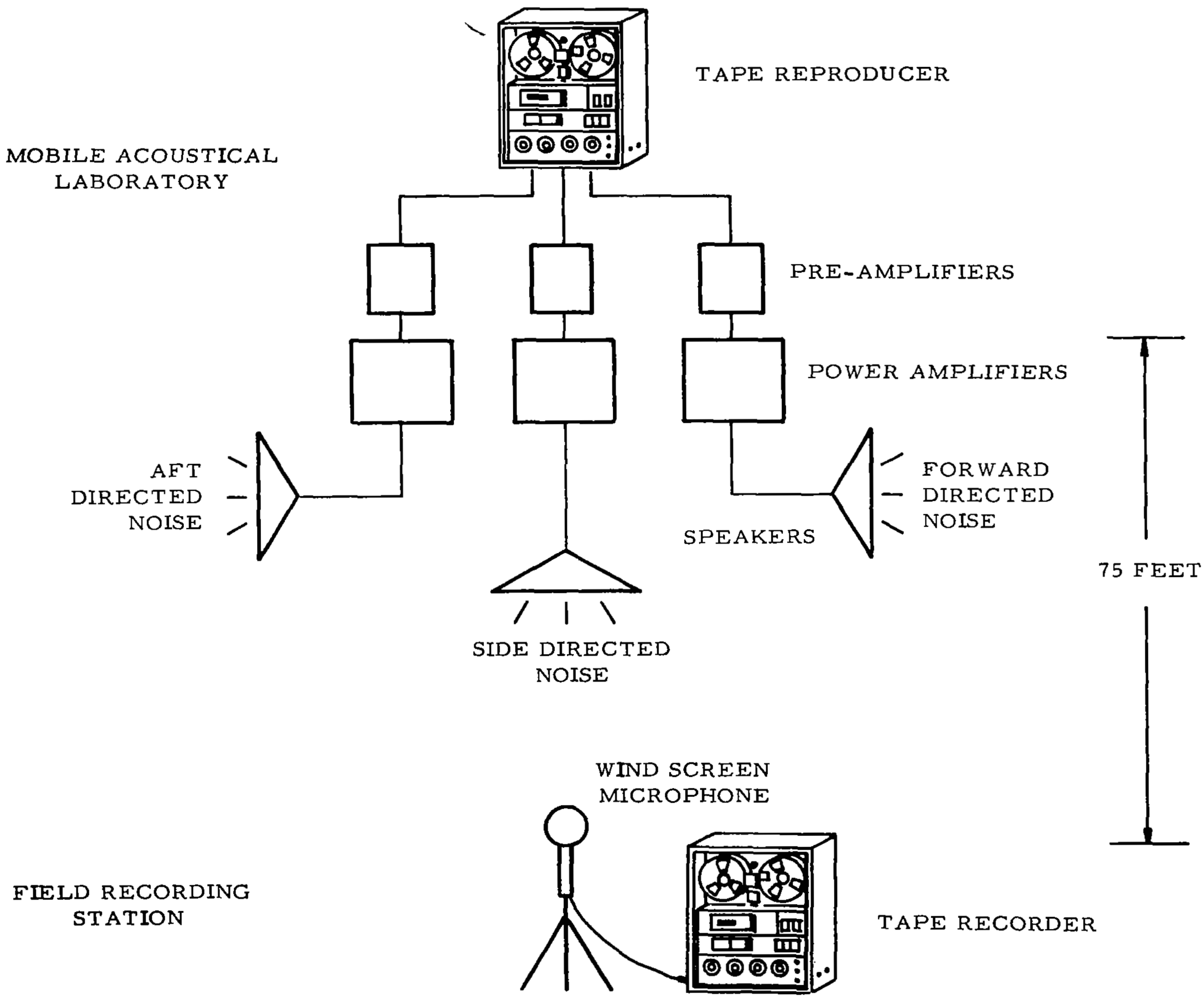


Figure 4. Field Synthesis of Aircraft Sound.

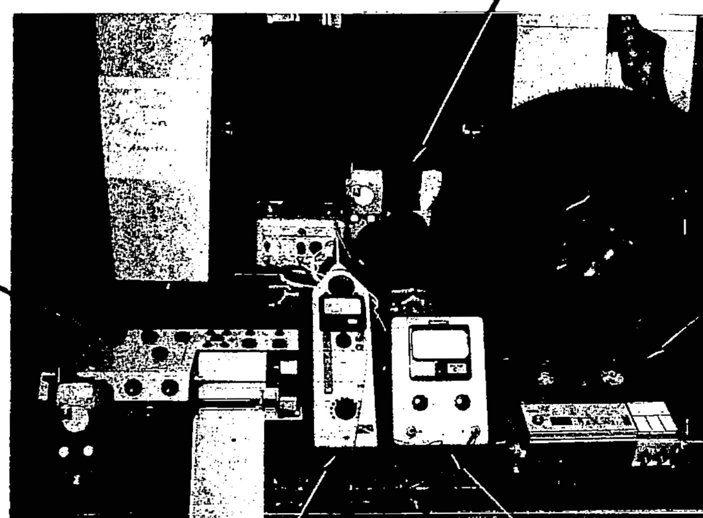


Figure 5. Field Spectrum Analysis.

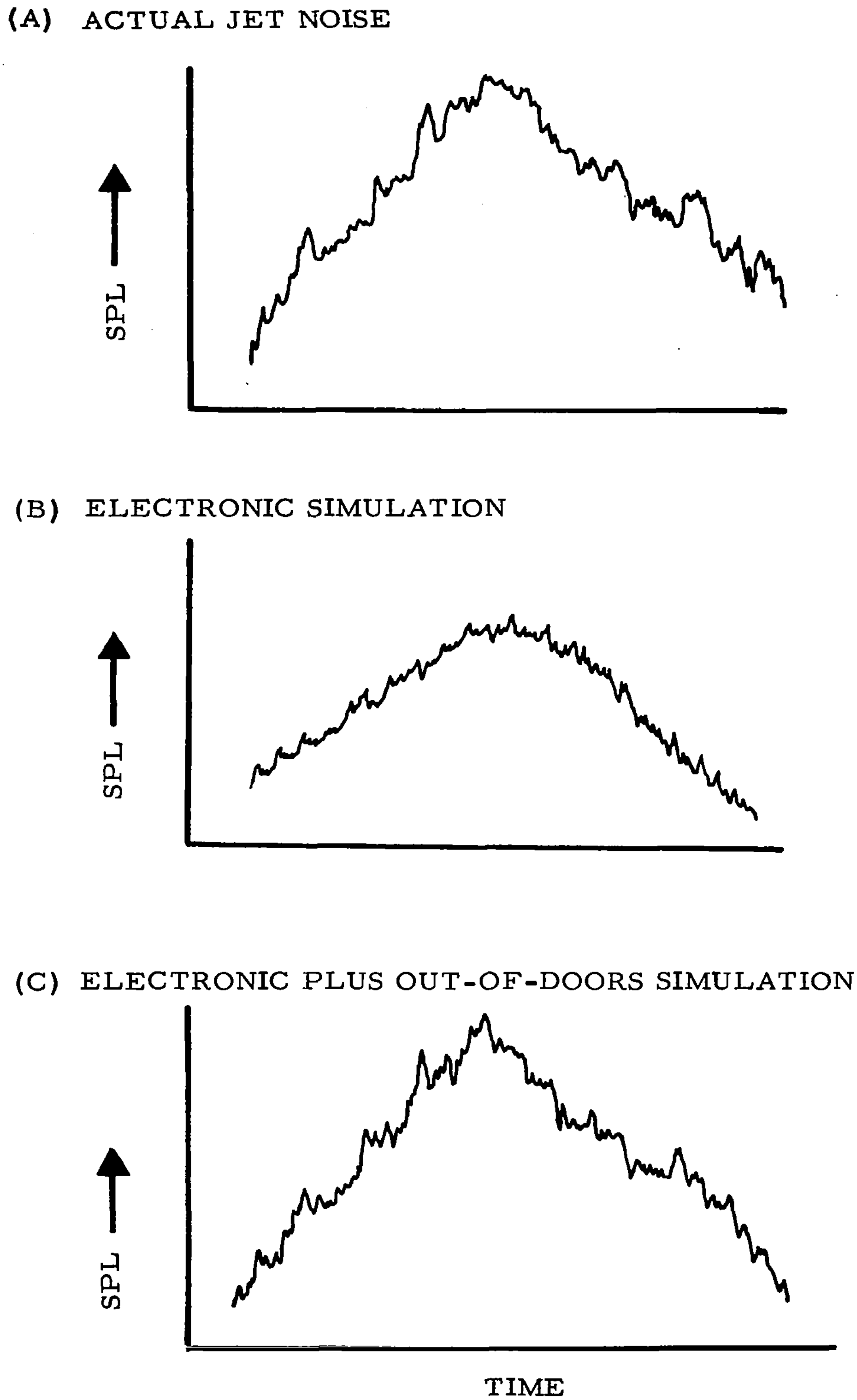


Figure 6. Amplitude-Time History of Cruise Noise.

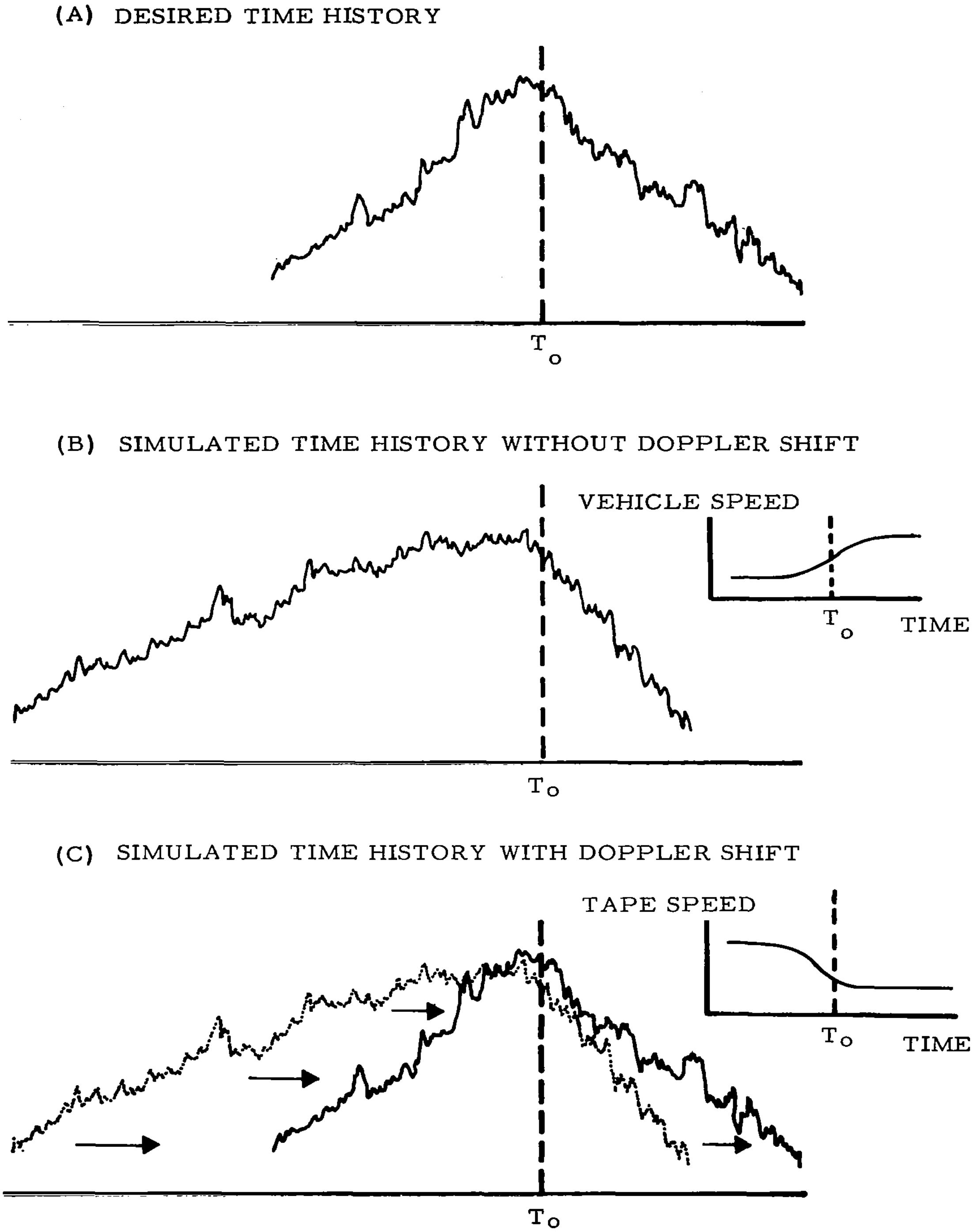
variations in the handling of the volume control are introduced. However, as illustrated in part c, the combination of an electronic sound with out-of-door fly-by simulation results in a most realistic simulation.

Based on the results of earlier experiments, it was decided to drive a microphone past a stationary sound source to simulate time amplitude variations. This was tried with the results that (1) wind noises created a problem even with protective devices like nose cones and wind screens, and (2) vehicle noises, being close to the recording microphone, were too high. Reversing the procedure and driving the source past the recorder minimized these problems.

Doppler shift. - It was assumed, because of the relatively low airspeeds required during hover-to-transition, that Doppler shift would make a relatively minor contribution to the overall subjective effect of the terminal noises. Its omission was felt to be justified in view of the work involved in inserting it into the sounds for these small speed variations. However, at cruise, this effect might become subjectively important and would certainly enhance the credibility of the simulated sounds. For those sounds requiring Doppler shift simulation, the following method for inserting this effect was used: the record made up of the component noises combined in the field by the vehicle fly-by technique was stretched on the approach and condensed on the departure sides of the peak of the amplitude-time history (Figure 7b). This was done by having the vehicle driven more slowly at the beginning than at the end of the simulated fly-by. Later, in the laboratory, this noise was re-recorded on the variable speed tape recorder (Figure 3g) at different tape speeds to obtain the desired overall frequency shift variation with time. Figure 7c illustrates this technique.

Final spectrum and amplitude-time history. - All that remained to be done was to adjust the octave band spectrum to its final envelope according to the predictions and to finalize the duration times between the 20 db downpoints (from the peak overall sound) by means of a potentiometer (Figure 3h and 3i).

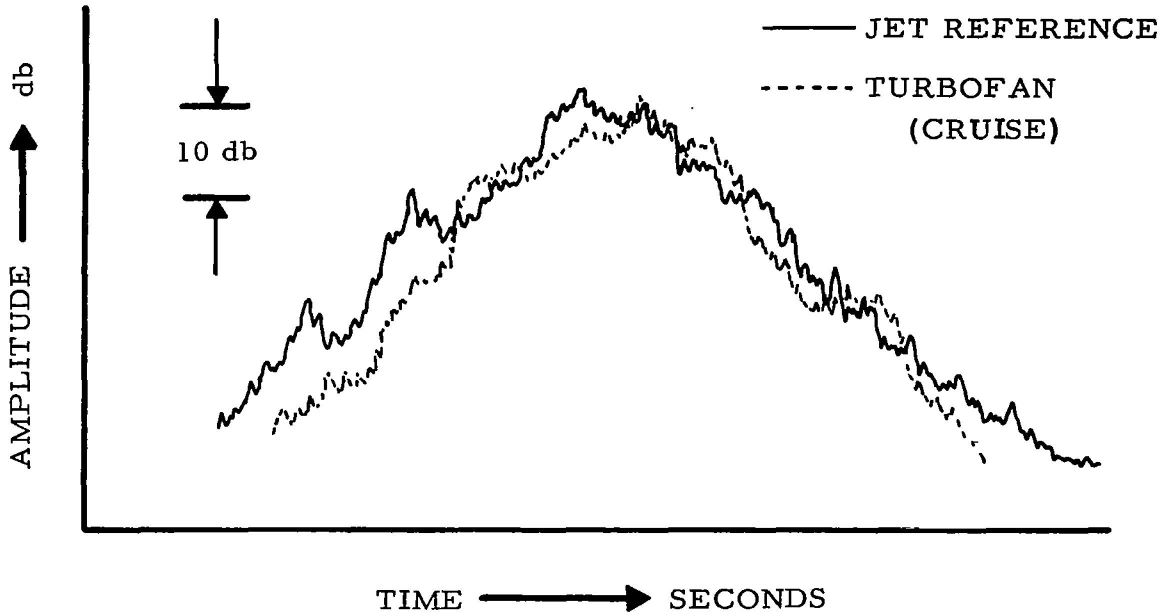
The amplitude-time history envelopes for the noise signatures representing an aircraft fly-over are very similar to that of today's jet airplane. Figure 8a illustrates such a typical transient of both the real jet sound, used as reference in the study, and that of one of the simulations. However, there is an obvious difference in these time histories and that of Figure 8b, which represents a takeoff noise history of a VTOL



NOTE: T_o = IS THE TIME WHEN AIRCRAFT IS CLOSEST TO OBSERVER

Figure 7. Simulation of Doppler Shift.

(A) CRUISE



(B) TAKE-OFF

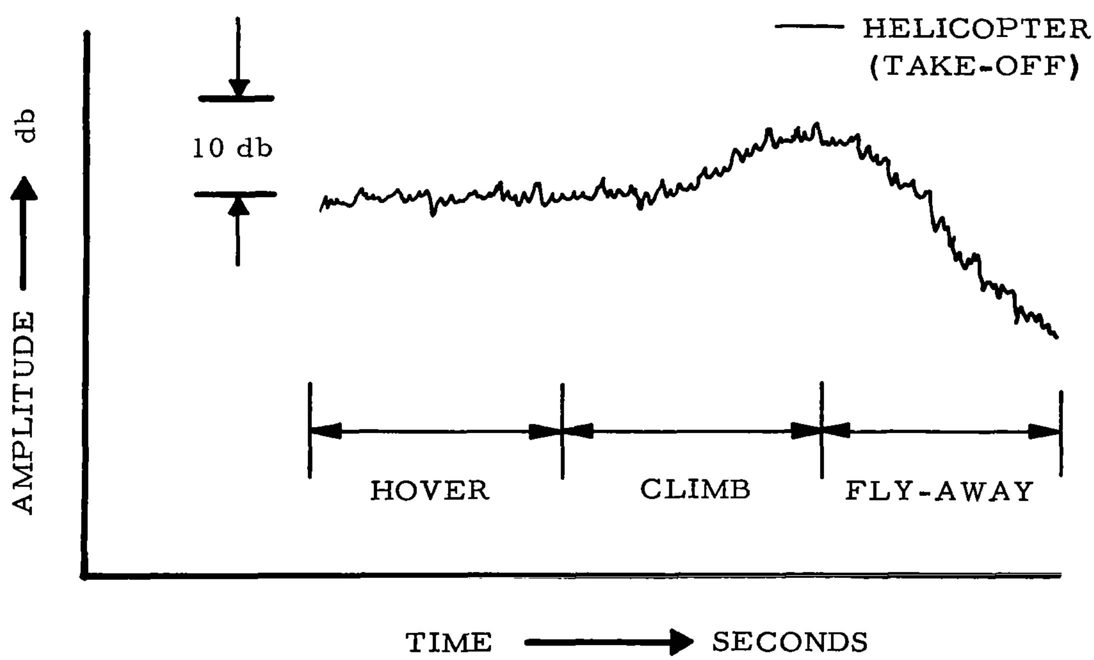


Figure 8. Comparison of Amplitude-Time Histories.

aircraft. The latter signature was determined from a study of motion pictures of helicopter takeoff operations from the roof of the Pan-American Building in New York City. The maneuver, considered typical of those which will be performed during VTOL takeoffs in urban areas, consists of the following: (a) hover for aircraft checkout, (b) vertical climb to 100 feet from the roof-top surface, and (c) fly-away. The average elapsed times for each of these flight portions determined from records of the roof-top operations was assumed to apply also for the VTOL aircraft in this study.

For a description of the synthesis of each individual aircraft sound, see Appendix B.

Volume Adjust Test

The general approach taken in this study required determination of the level of a given sample of noise that is judged to be equally annoying to the reference sound of the jet airplane. Since the amount of testing which could be performed was limited to about two hundred test subject hours, each curve had to be defined by only four points of data, and the response curves with these few points presented two problems:

1. The spread of test levels must be large in order to ensure inclusion of the 50 percent decision point within the range tested.

2. The spacing of the points should be close enough to allow good definition of the 50 percent decision point.

It is obvious that the two requirements are in conflict, but the spread of test levels could be greatly reduced if it were possible to define the 50 percent decision point by preliminary testing, and then refine the definition in this area with the large sample test program.

In order to achieve the first objective, a preliminary test, called the volume adjust test, was performed. Subjects were asked to listen to the reference and stimulus sounds in succession as many times as they wished and to adjust the volume of the stimulus to a level which produced equal annoyance to the reference. The volume of the reference, a jet airplane sound of 112 PNdb out-of-doors, could not be adjusted.

The median of the subjective response was then chosen as the midpoint from which the four levels for the paired comparison tests were derived. Appendix C describes the procedure used to simulate apparent distance effects for each of these four levels.

SUBJECTIVE TESTING

Preliminary Test

The purpose of a preliminary test using Company subjects was to ensure that good test results could be expected during the paired comparison tests at the college site. Therefore, the final test tape, in the format to be used on the student subjects, was played to a group of in-house subjects, and the results were analyzed.

The following instructions were both read and provided to each listener in writing prior to his partaking in the test:

"The purpose of these tests is to determine the relative acceptability of different sounds. The tests are part of a program of research designed to obtain information that would be of aid in planning for future aircraft.

"You will hear, on the recording to follow, one sound followed immediately by a second sound. You are to judge which of the two sounds you think would be the most disturbing if heard regularly, as a matter of course, 20 to 30 times per day in your home. If you think the first of the two sounds would be more disturbing, put a check mark in the first box after the number announced before each pair of sounds (☑ ☐). If you think that the second of the two sounds would be more disturbing, put a check mark in the second box (☐ ☑). If you think they would be equally disturbing, please make a choice even though you feel you are guessing.

"Remember, your job is to judge the relative unwantedness of the two sounds. You may think that neither of the two sounds is objectionable, or that both are objectionable; what we would like you to do is judge which sound would be more disturbing than the other if heard in your home periodically 20 to 30 times during the day and night.

"Please record your answers according to how the sounds affect you - there are no right or wrong answers, and it is important that we find out how people differ, if they do, in their judgments of these sounds. It does not matter whether your answers agree or disagree with others taking this test as long as you make the best judgment you can for each pair of sounds."

The design of a survey form is an important part of the total presentation to a test subject. Improperly designed forms can lead to problems with respect to confusing a test subject or, even worse, biasing the answers through choice of wording or physical layout. Figure 9 shows the form used.

Subjective Testing

Since the acoustical environment in which the tests were conducted formed a very important part of the subjective aspects in this psycho-acoustical experiment, it was necessary to ensure that the room contemplated for use in the test did not exhibit any undesirable acoustical qualities. The chosen room approximated a good acoustical test environment due to the presence of acoustical ceiling tile, wall-to-wall carpeting, heavy wooden doors and thick glass windows. The room was air-conditioned.

The sound reproducing system for the final tests consisted of a tape playback unit whose output was shaped with the one-third octave band equalizer to compensate for systems linearity and room acoustics. This shaped spectrum signal was then amplified and fed to the speaker facing the test subjects. (See Figure 10.)

Since the noises produced from the large speaker and heard by the test subjects were to be re-recorded for later correlation studies, a microphone was placed near the center of the room and inside the acoustically acceptable area. The microphone signal, tape recorded for later detailed laboratory analysis, was also monitored during the entire testing with an octave band spectrum analyzer and graphic level recorder. Absolute sound level calibrations were performed with the aid of a piston phone before and after each test to check the performance of all instruments, and, as a double check on the graphic and magnetic recording system, an independent sound level meter was employed during all tests to check overall levels.

The equipment in the test room was arranged so that the test subjects faced the speaker in one corner of the room.

NAS-7083 TEST II SERIES ______ SUBJ. ____________________

FOR EACH PAIR CHECK WHICH SOUND YOU THINK IS MORE DISTURBING.

Pair No.		1st	2nd	Pair No.		1st	2nd	Pair No.		1st	2nd
1	______	☐	☐	17	______	☐	☐	33	______	☐	☐
2	______	☐	☐	18	______	☐	☐	34	______	☐	☐
3	______	☐	☐	19	______	☐	☐	35	______	☐	☐
4	______	☐	☐	20	______	☐	☐	36	______	☐	☐
5	______	☐	☐	21	______	☐	☐	37	______	☐	☐
6	______	☐	☐	22	______	☐	☐	38	______	☐	☐
7	______	☐	☐	23	______	☐	☐	39	______	☐	☐
8	______	☐	☐	24	______	☐	☐	40	______	☐	☐
9	______	☐	☐	25	______	☐	☐	41	______	☐	☐
10	______	☐	☐	26	______	☐	☐	42	______	☐	☐
11	______	☐	☐	27	______	☐	☐	43	______	☐	☐
12	______	☐	☐	28	______	☐	☐	44	______	☐	☐
13	______	☐	☐	29	______	☐	☐	45	______	☐	☐
14	______	☐	☐	30	______	☐	☐	46	______	☐	☐
15	______	☐	☐	31	______	☐	☐	47	______	☐	☐
16	______	☐	☐	32	______	☐	☐	48	______	☐	☐

Figure 9. Test Form.

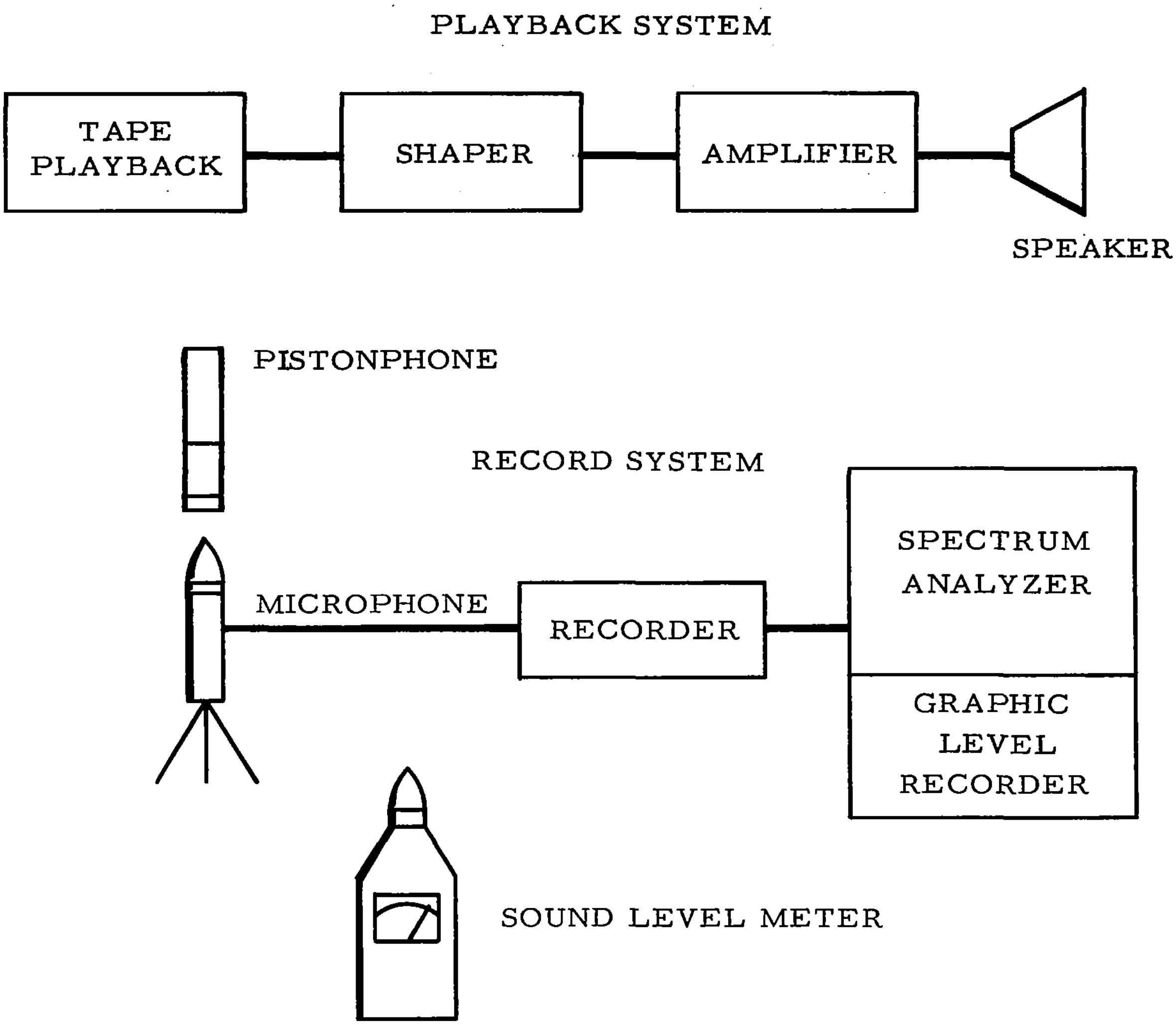


Figure 10. Subjective Test Sound Reproducing Equipment.

To prevent undue distractions, the playback and record instrumentation was placed at the rear of the room. Figure 11 presents views from the rear and the front of the room, respectively.

The test procedure used at the college was identical with that administered previously in the laboratory with Company subjects. Instructions were given and the tests supervised by a qualified experimental psychologist to ensure the proper conduct of the test.

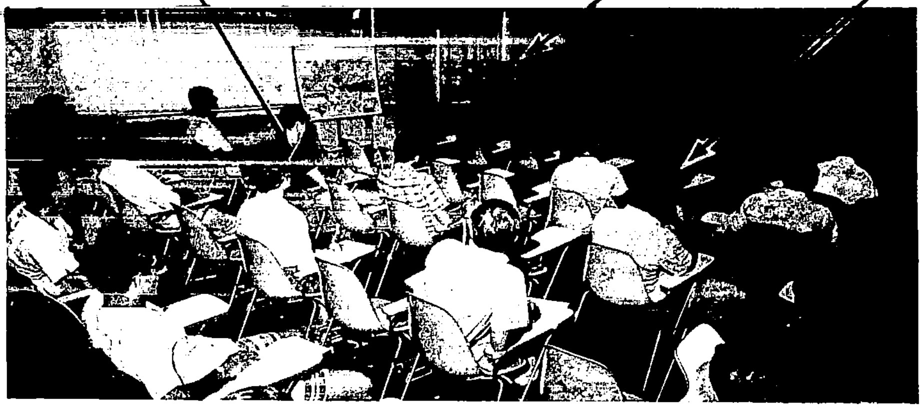
EVALUATION OF RESULTS

Comparison of Jet Airplane with Future V/STOL Aircraft

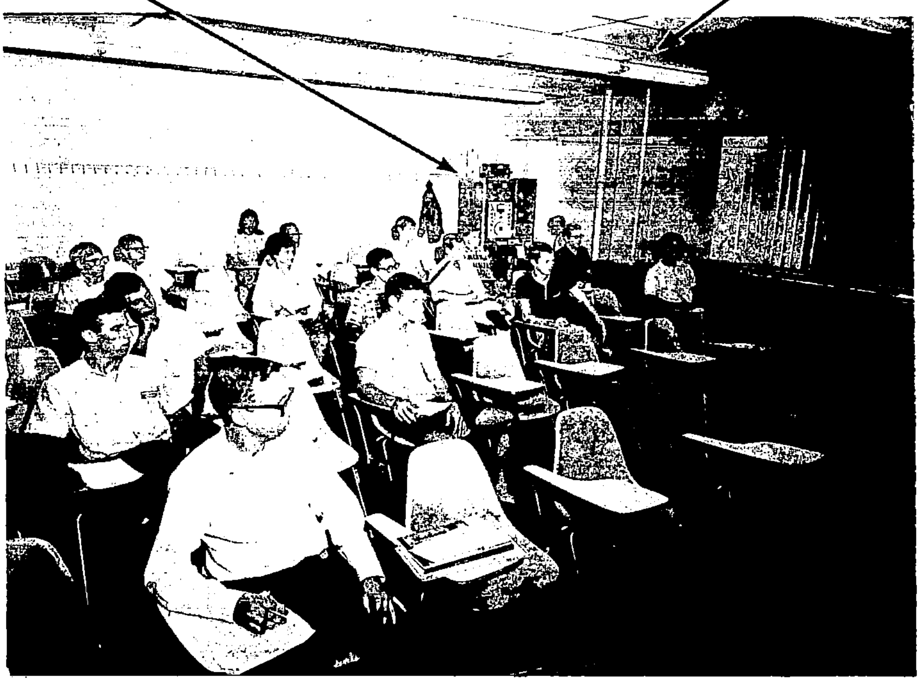
Acoustic data analysis. - The recordings made during the subjective testing were analyzed into octave bands. An exact matching of simulated and predicted aircraft spectra was not achieved, probably due to sound absorption of test subjects. However, since the 50 percent point from the subjective response curves is of primary interest to the objectives of this study, the only concern was that the test sound levels were to be distributed about this point (see Figure 12).

Subjective data analysis. - Of the total subjects exposed to the paired comparison test, 82 of the male college students were considered valid test subjects. The Chi square test was used to perform a statistical analysis of the relative homogeneity of the larger test groups with respect to the number of times the stimulus was judged more annoying than the reference for all four levels of intensity (loudness). This analysis was done for both procedures, i.e., reference first, stimulus second, and stimulus first, reference second, making a total of 24 analyses. In all cases, the Chi squares were not statistically significant ($P > .05$), indicating that the smaller groups tested could legitimately be combined into one group and the data treated as a whole. Subsequent analyses were therefore carried out using the combined total group ($N = 82$).

The response of the homogeneous group was separated according to the position of the reference sound in each of the pairs used in the comparison test. The effect of the relative position of sound in a given sequence is discussed in Appendix C. Since the direction and magnitude of the subjective shift in rating scale can be predicted only qualitatively for a given test



(A)



(B)

Figure 11. Subjective Test Room.

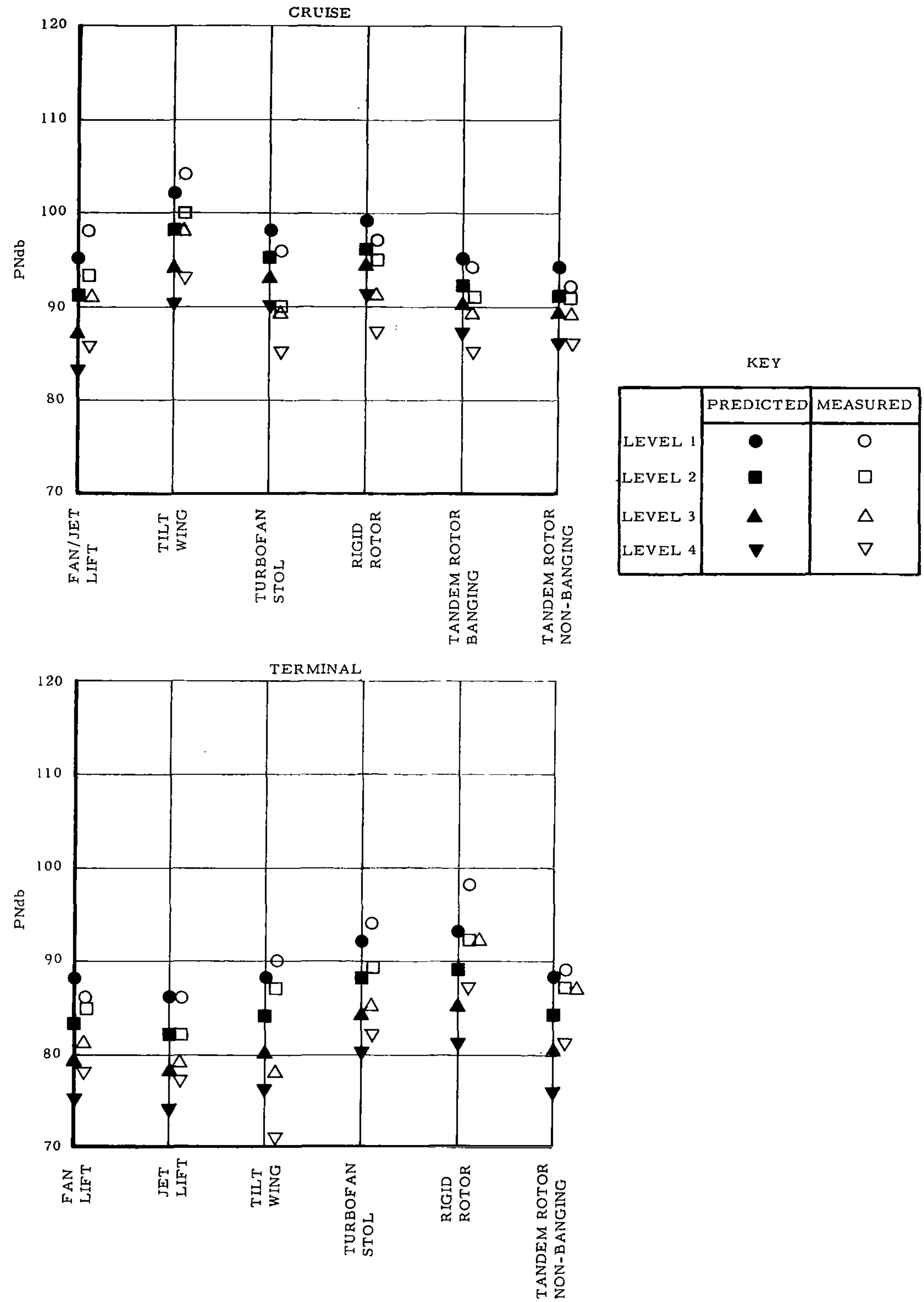


Figure 12. Comparison of Simulated and Predicted Aircraft Sounds.

situation, the effect was kept separate throughout the analysis to determine the comparative perceived noise level of each aircraft sound.

Derivation of comparative peak PNdb. - The percentage of test subjects who thought that a stimulus was more disturbing than the jet reference is presented along with the corresponding peak perceived noise level measured in the test room. Appendix D is the result of this correlation.

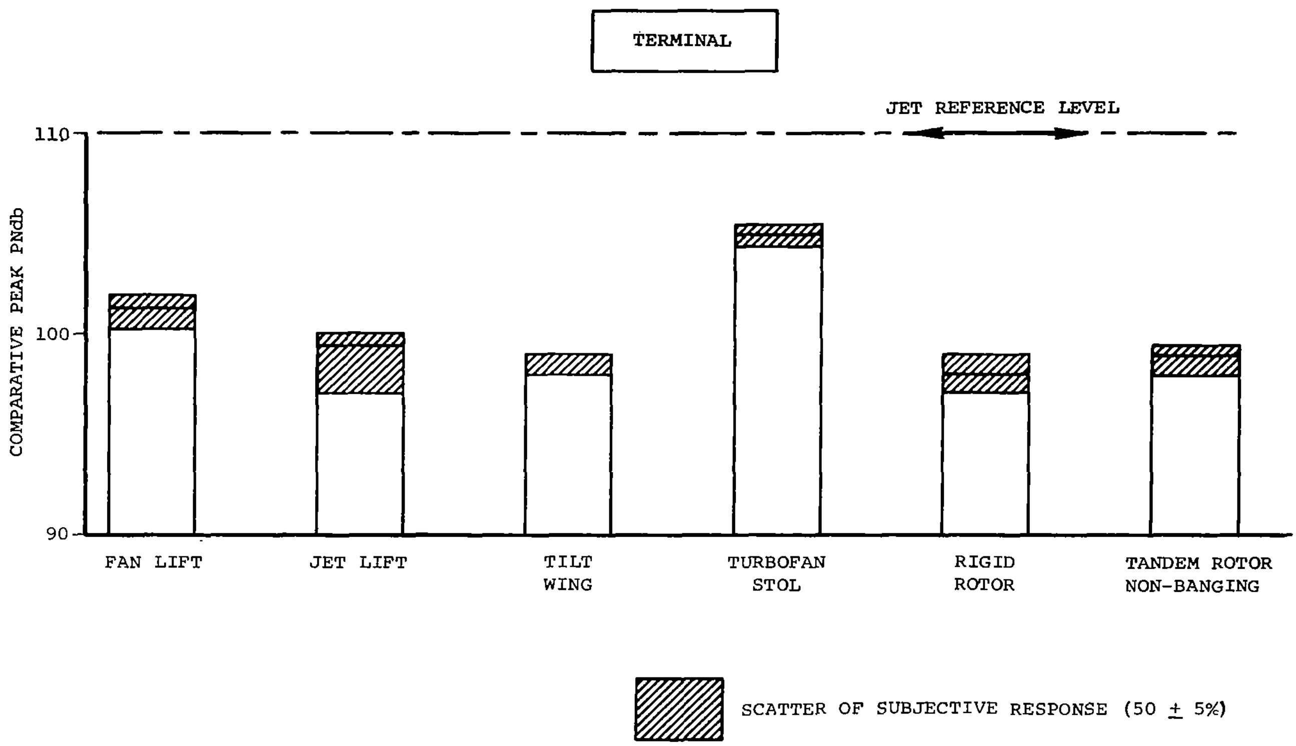
While a determination of the indoor comparative peak perceived noise level is primarily of psycho-acoustical interest, the results of this study applied to the predicted outdoors sounds are of much more practical interest to the aircraft designer and operator. The distinction between a test where outdoor subjects listen to and rate outdoor sounds and this investigation should, however, be retained. The prime differences are that it will be the aircraft external noise levels which are amenable to more accurate prediction methods than people's responses to them, and that it is the reaction of people inside a dwelling which will evoke a more meaningful and important response than that from out-of-door listeners.

Hence, it is of quite some importance to know the relative annoyance of different types of aircraft noise including that of the jet reference based on out-of-door criteria. Therefore, the response of indoor listeners to an out-of-door sound, simulated as it would be heard indoors, is used to predict the relative annoyance of the various V/STOL aircraft in this study.

Appendix E illustrates the derivation of comparative peak perceived noise level of the outdoor aircraft sounds in this study. The 50 percent subjective response point, when termed in peak PNdb, is the comparative peak PNdb of that class of aircraft sounds represented by the spectra used in this study and is relative to the jet aircraft sound of today. The subjective results are summarized in Figure 13, where a plus and minus five percent scatter of the subjective response about the midpoint is indicated by the cross-hatched portions of the data.

Some Aircraft Operational Considerations

In the description of the process of simulating aircraft noise spectra by apparent distance effects, it was noted that the four levels of each of the twelve aircraft sounds represented



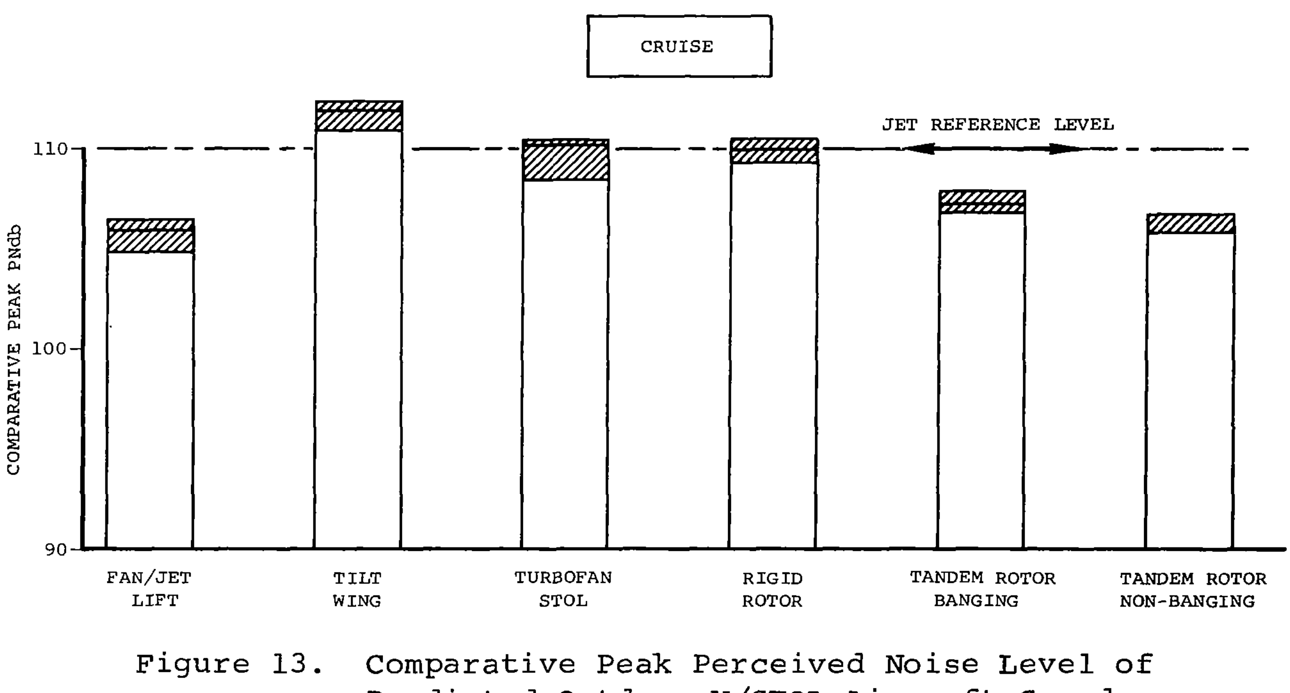


Figure 13. Comparative Peak Perceived Noise Level of Predicted Outdoor V/STOL Aircraft Sounds.

a realistic noise level at a particular distance from an observer. The distance at which each aircraft produces its comparative peak perceived noise level is shown in Figure 14. Part (a) of the figure indicates that the fan lift VTOL, for example, has to conduct terminal operations at a horizontal distance of approximately 2700 feet from the nearest occupied dwelling in order not to exceed its comparative peak PNdb. Similarly, in part (b) of the figure, the same aircraft when in the cruise configuration has to maintain an altitude of 1200 feet above the highest geographical point of public acoustic sensitivity.

Some degree of uncertainty in the data of Figure 14 is indicated by the length of the brackets and is derived from the plus and minus five percent subjective response scatter about the midpoint. The PNdb number next to the brackets indicates the comparative perceived noise level of each aircraft type rated subjectively. Also given are the perceived noise levels which each aircraft type would produce at specified distances if no noise reduction techniques were applied.

Specific Source Noise Reduction

Calculation procedures. - Substantial distances between aircraft and the public are involved when an attempt is made to retain comparative noise levels at today's limits without attempting aircraft source noise control. To relieve these constraints in order to permit lower or closer operation, it is clear that the results of this study can be used to form a guideline for areas and amount of noise reduction required by application of the following procedures:

1. Set target altitudes (or distances)
2. Calculate PNdb predicted at these altitudes (or distances)
3. Subtract comparative PNdb from item 2 to determine the perceived noise level reduction required
4. Examine sound spectrum of each component to determine its effect on perceived noise level
5. Successively reduce the predominant source until a different source becomes primary in setting perceived noise level
6. Repeat until the desired PNdb is attained

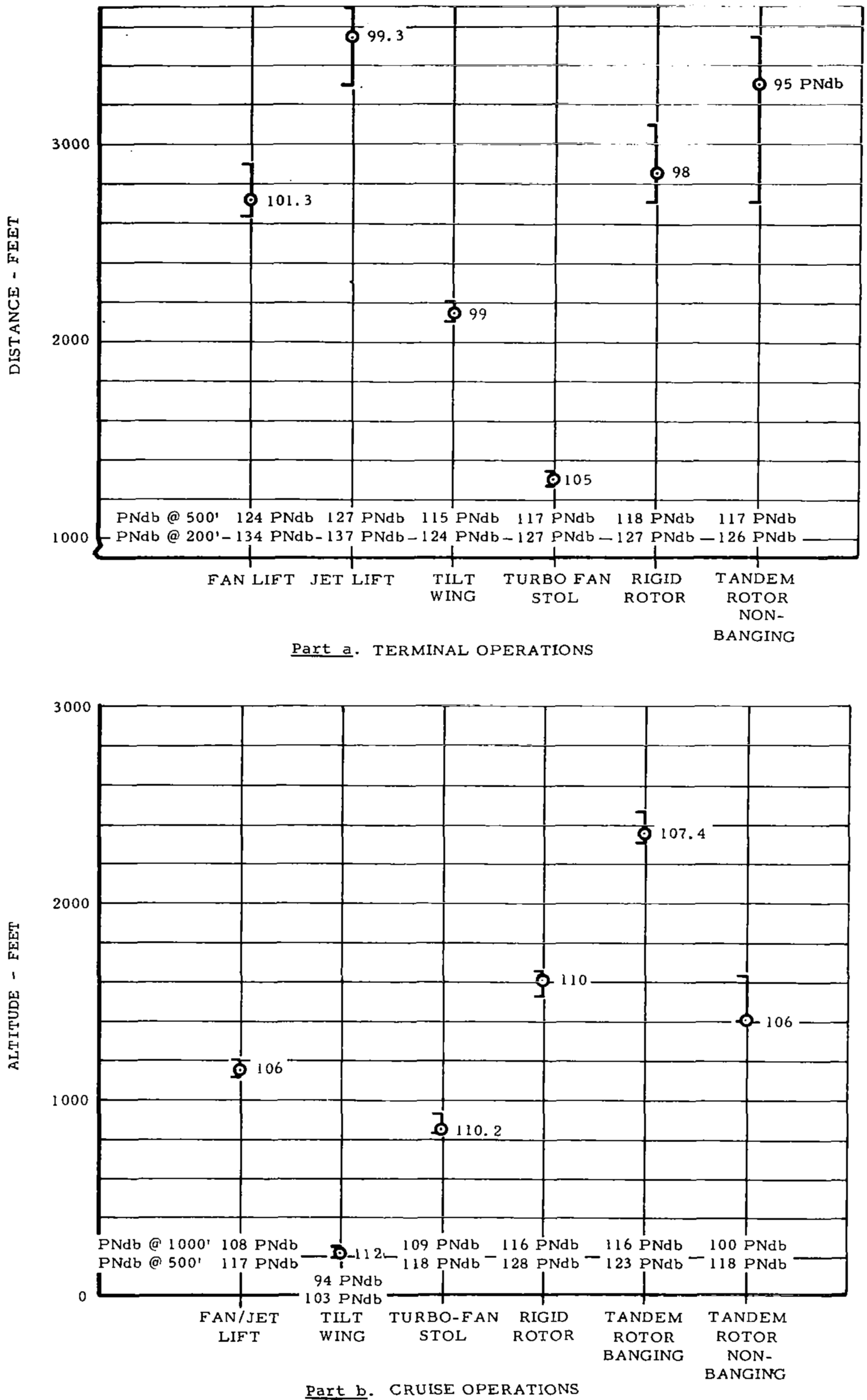


Figure 14. Distance (Altitude) at Which Aircraft Produce Comparative Peak PNdb.

Noise reduction requirements. - Each vehicle was examined for two altitudes (1000 feet and 500 feet) in cruise, and for two horizontal distances (500 feet and 200 feet) in the terminal phase of operation. In each case, the first number probably represents a feasible requirement and the second an optimistic target which should more than satisfy minimum demands. Table I presents the result of this analysis for each aircraft and the distances at which operation is desired. The following comments are made relative to the noise reduction requirements shown in Table I.

Terminal noise.

Inlet noise. - During terminal operation, the fan lift type of VTOL aircraft requires a 25 to 35 decibel reduction in cruise engine intake noise, depending on whether the aircraft is 500 or 200 feet away from a noise sensitive area. The decibel figures represent a reduction of radiated sound of up to 98 percent. It is clear that these are substantial amounts and could only be met with extreme technological efforts. An even greater requirement in this area is posed by the jet lift type of VTOL aircraft, which requires a 30 to 40 decibel reduction or attenuation of far-field inlet noise. The remaining V/STOL aircraft types have a somewhat less severe demand in this area, but will nevertheless prove difficult to adapt to the proposed requirements. The lift fan and gas generator intake noise problems of the fan lift VTOL aircraft will certainly benefit from noise reduction techniques applicable to cruise engine inlets in general.

Exhaust noise. - The other cruise engine noise source requiring reduction is the exhaust. Relatively minor noise reduction figures have been achieved to date compared to the potential of reducing the inlet noise. The most effective methods of diminishing the broad-band frequency acoustic radiation levels are to lower the temperature of the exhaust gases and/or their velocities, steps which usually impose unacceptable efficiencies on this type of propulsion system. The use of by-pass types of powerplants tends not only to result in increased thrusts compared to straight jets, but also a lowering of the mean jet velocities and gradients with respect to ambient air. The reduction of these velocities also results in appreciable exhaust noise reductions. Whereas these techniques have already been assumed in the V/STOL aircraft designs in this study, further exhaust noise reductions of 5 and 10 decibels of

TABLE I

COMPONENT NOISE REDUCTION REQUIRED
TO OPERATE AT SPECIFIED DISTANCES AND ALTITUDES
WITHOUT EXCEEDING COMPARATIVE PEAK PERCEIVED NOISE LEVEL

Part a: Terminal

Target Distance: 500(200) Ft						
	Aircraft Class					
Noise Component	Fan Lift VTOL	Jet Lift VTOL	Tilt Wing VTOL	Turbofan STOL	Rigid Rotor VTOL	Tandem Rotor VTOL (No Bang)
	Required Decibel Reduction					
Cruise Engine						
Intake	25(35)*	30(40)	15(30)	15(30)	15(30)	15(30)
Primary Exhaust				5(15)		
By-Pass Exhaust				10(15)		
Deflected Exhaust	10(20)	15(20)				
Lift Engine						
Intake		30(40)				
Primary Exhaust		15(25)				
By-Pass Exhaust		10(20)				
Propeller						
Rotational			15(25)			
Vortex			15(20)			
Rotor						
Main						
Rotational					20(30)	15(25)
Vortex					20(30)	15(25)
Tail						
Rotational					15(25)	
Vortex					15(25)	
Gas Generator						
Intake	20(35)					
Control Nozzle						
Exhaust	15(25)					
Lift Fan	28(40)					

* The first number refers to reductions required for 500-foot operation. The number in parentheses refers to 200-foot operation.

Part b: Cruise

Target Altitude: 1000(500) Ft						
	Aircraft Class					
Noise Component	Fan/Jet Lift VTOL	Tilt Wing VTOL	Turbofan STOL	Rigid Rotor VTOL	Tandem Rotor VTOL (Bang)	Tandem Rotor VTOL (No Bang)
	Required Decibel Reduction					
Cruise Engine		No Reduction Required				
Intake	2(14)*		(10)	10(18)	(10)	(10)
Propeller						
Rotational				5(10)		
Vortex				7(15)		
Rotor						
Rotational					5(10)	5(10)
Vortex					5(10)	5(10)
Blade Bang					10(10)	

* The first number refers to reductions required for 1000-foot cruise altitude operation. The number in parentheses refers to 500-foot operation.

the primary and by-pass exhausts of the turbofan STOL are necessary to permit operation within reasonable distances. Both of these figures need to be raised to 15 decibels for 200 foot terminal operation.

While the 5 to 10 decibel reduction requirements are probably feasible today and could thus make the turbofan STOL aircraft acceptable, reductions on the order of 15 to 25 decibels necessary for several other V/STOL aircraft types are quite demanding. Reductions in noise level of deflected cruise engine exhausts represent a significant design challenge in view of the complex mechanisms involved. The primary and by-pass exhausts of the jet lift VTOL lifting engines will pose one of the greater problems in terms of fundamental noise control techniques.

Propellers and rotors. - In other areas of V/STOL aircraft noise control, the problems of propeller and rotor noise appear. Tilt wing rotational and vortex propeller noise will have to be reduced at least 15 decibels to permit hover operations during terminal approach and departure, even at 500 feet distance. The requirements for 200 foot operation are even more severe, from 20 decibels of vortex noise reduction to 25 decibels for the discrete frequency rotational noise. Other problems may yet arise in the area of effects on noise from propeller overlap, disc to disc gap, and ground effects.

Helicopter rotor noise is generally not predictable by application of the methods which work well for propeller noise. Although research in the area of rotor noise has recently become more active, reductions of the order of magnitude shown in Table I are yet to be demonstrated.

The torque compensating tail rotor of helicopters with a single rigid rotor requires a 15-decibel reduction in noise. Another 10-decibel reduction for each component would be required for 200 foot operation. Since single rotor helicopters have a generally larger main rotor diameter than corresponding tandem rotor types, it might be concluded that with the generally lower blade passage frequencies of the former a more benevolent subjective effect could be expected based on the perceived noise level curve. The experimental and analytical discrepancies between these expectations and the data in the required noise reduction tabulation are probably due to the pulsating nature of the blade passage noise, an effect which may tend to be more annoying with lower repetition frequency.

Cruise noise.

During low altitude cruise operations, the tilt wing type of VTOL aircraft as described in this study does not require any noise reduction. This is primarily due to the relative subjective acceptability of its conventional, and rather well known, propeller type of noise. The reduction of blade tip speed from 850 to 500 feet per second is apparently quite sufficient to make this aircraft acceptable even at a 500-foot altitude. A related configuration, the rigid rotor VTOL that becomes a conventional propeller airplane in cruise, requires a 5- to 7-decibel reduction in propeller rotational and vortex noise for fly-over operation at 1000 feet, and correspondingly 10 to 15 decibels for 500 foot operation. In addition, depending on the desired target altitude, engine inlet noise has to be reduced 10 to 18 decibels. The propeller noise reduction requirement could probably be lowered if the blade tip speed were reduced; also, more favorable engine location might yield a relatively simple solution to the inlet noise problem. Inlet noises from the other configurations need serious attention only if cruise operation at a 500-foot altitude is required. The requirements are, however, not so restrictive that whatever feasible solutions are offered for the corresponding terminal noise situation could not be applied here also.

Reduction of tandem rotor helicopter blade rotational and vortex noise by 5 decibels each would permit operation at 1000-foot altitude. The banging tandem rotor helicopter has to be transformed into a nonbanging rotor VTOL aircraft. This can be achieved by appropriate blade pitch controls and will thus be able to meet the noise reduction requirement of 10 decibels for both 1000- and 500-foot operation.

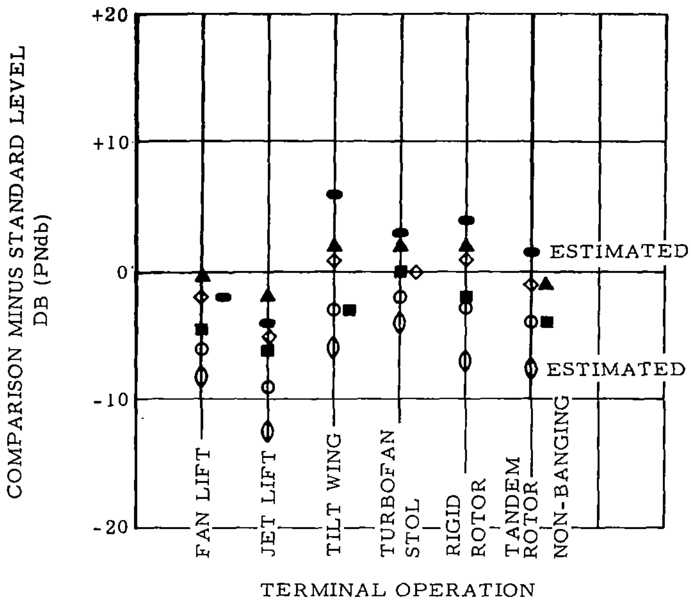
The information derived for each vehicle can thus serve as the guideline for required research into future noise reduction along with the amount of noise reduction for each component. If operations at the specified target distances require unrealizable amounts of component noise reductions, other measures must be used. These may include such techniques as decreasing noise exposure time by improved instrumentation and operational procedures which permit the aircraft to load and unload passengers faster.

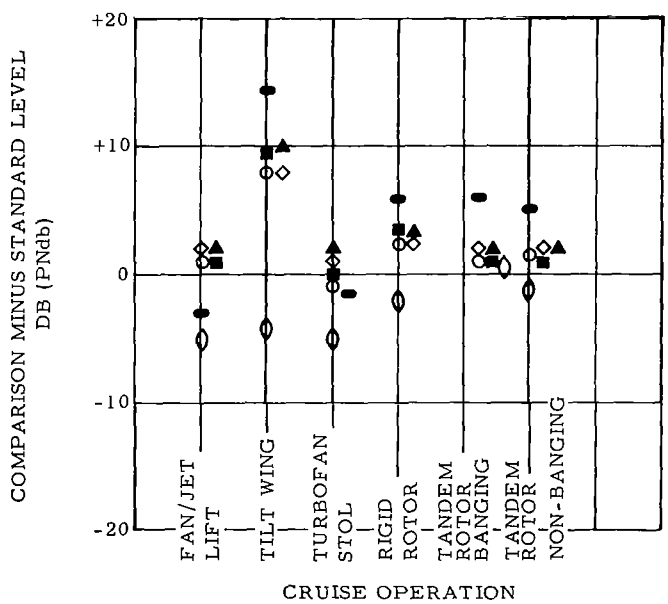
Other Noise Rating Methods

dBC and dBA levels. - The frequency-weighted electronic networks labeled C and A scale on most sound level meters were used to measure the indoor simulated noises during subjective testing. The C network is essentially flat over the audio range while the A network more closely simulates the responses of the human ear. Figure 15 indicates the difference in decibels between the stimulii and the jet reference when these weighting methods are applied to the stimulii. Based on the average of the difference between the stimulus and the reference, and the standard deviation of this average of each rating method, the db A and C scales do not correlate as well as PNdb.

Tone and duration corrections. - There is general agreement among acoustical researchers that a noise rating method which accounts for discrete tones and sound duration is required. The extent of the corrections, however, has not been recognized as definitive or absolutely applicable by enough authoritative agencies or groups to conclude that any particular correction method published to date will be acceptable to the majority of noise-conscious control bodies. Still, it was felt desirable to obtain a magnitude estimation of tone and duration corrections for the particular sounds in this study. Therefore, the method of determining the corrections for this example was adopted from "Proposed FAA Maximum Allowable Noise Levels to be Required for Certification of Future Aircraft," dated 26 August 1966.

In the proposed requirements, it is stated that, to account for effects of duration, a factor D be defined as ten times the logarithm of the ratio of the duration of a sound to be evaluated to the reference duration time of a standard jet noise, the latter defined as 15 seconds. The duration of the sound to be compared is based on the length of time it takes for the sound to build up from 15 decibels before it reaches its peak perceived noise level to 15 decibels after the peak has been attained. The factor D is to be added to the peak perceived noise level as computed conventionally from a third-octave band analysis of the test sound. It is clear, then, that a sound which lasts longer than the reference jet will be assigned a higher PNdb rating, and a sound lasting less time will have a lower PNdb number assigned to it. Termed somewhat differently, a penalty of 3db will be added for each doubling of time above 15 seconds, and a credit of 3db will be subtracted for each halving of time.





	RATING METHOD
PEAK PNdb - 50% POINT	○
PEAK PNdb TONE CORRECTED	■
PEAK PNdb DURATION CORRECTED	◇
PEAK PNdb TONE AND DURATION CORRECTED	▲
dBA	0
dBC	⬬

OPERATION	RATING METHOD	AVG. DIFF.	STD. DEV.
TERMINAL	○	-4.41	1.85
	■	-3.3	1.85
	◇	-1.0	2.1
	▲	+0.58	1.58
	0	-6.33	2.8
	⬬	+1.41	3.76
CRUISE	○	+2.14	2.8
	■	+2.58	3.27
	◇	+2.91	2.28
	▲	+3.5	3.7
	0	-2.75	2.08
	⬬	+4.8	5.68
TERMINAL AND CRUISE	○	-1.1	4.2
	■	-0.37	2.73
	◇	+1.0	2.82
	▲	+1.45	2.9
	0	-4.54	3.2
	⬬	+3.1	5.0

Figure 15. Comparison of Noise Rating Methods.

A pure tone correction factor is also proposed and is derived experimentally using test subjects in a procedure like the one used to originally derive the perceived noise data. The pure tone correction is made to account for the fact that a random noise containing discrete frequency or pure tones, such as engine inlet noise, is more objectionable to a listener than a broad-band noise, such as jet exhaust noise, even when both types of sound result in the same measured PNdb value.

No effort was made during this study to have the V/STOL aircraft meet the proposed FAA criteria, primarily because the criteria as written is not directly applicable to V/STOL's. Also, the effort would have been outside the scope of this investigation. Several interesting results emerge, however, when the correction factors are applied to V/STOL aircraft sounds. In Figure 15, which compares several rating methods, the jet reference sound of this study was used as the standard and the sounds to be compared were the six terminal operation noises and the six cruise noises. For each rating method used, the characteristics of the standard jet sound were first determined and formed the basis for comparing the other sounds. For example, the rating method identified as "Peak PNdb - Duration Corrected" was based on the factor D as described before, using the duration of the standard sound (in this case, 17 seconds) to determine the amount of deviation in computed decibel levels between the comparison and standard sounds. This difference, sometimes positive, sometimes negative, depended on which aircraft sound was being compared. The differences between the standard and each of the twelve V/STOL aircraft sounds is plotted in Figure 15. The average difference between the standard noise and the V/STOL terminal noise, cruise noise, and combined terminal and cruise noise, along with their standard deviation from the average difference, is shown in the tables accompanying Figure 15.

Although the statistical evaluation on Figure 15 does not show any greatly significant effects of the corrections, this is not necessarily true for individual cases. In fact, these corrections can only be evaluated for those specific cases to which corrections apply. Since the cruise operation involves elapsed times close to 15 seconds, no correction is evident. The terminal operation, however, involves substantially longer times, and an improvement in correlation, due to inclusion of duration correction, is noted in all cases.

In order to minimize the time duration penalty, it seems appropriate to investigate every aspect relating to the duration of an aircraft noise and its cause. Among these are: reduced terminal operating procedures for passenger and cargo handling for shorter turn-around times; faster propulsion system response to obtain safe flight status after ground-idle; or even improved cockpit instrument displays to facilitate check-out by the pilot during the critical flight path portions of landing and takeoff of any aircraft, but especially V/STOL aircraft.

Pure tone components are most strongly evident during terminal operations of the fan lift, jet lift, and turbofan STOL aircraft. In these cases, a significant improvement in correlation is indicated by inclusion of the pure tone correction factor.

CONCLUSIONS

The success of commercial V/STOL aircraft short-haul transportation for the 1970's is considerably dependent on public acceptance of the noise generated during terminal and cruise operational phases of aircraft flight (see also reference 16). Some V/STOL aircraft configurations exhibit better acoustical characteristics than others due to inherent differences in design configuration and propulsion systems (see Figure 13). The quantitative guidelines for the evaluation of public reaction to the noise of these configurations were established based on correlation of both subjective and objective measurements of predicted and electronically synthesized aircraft sounds.

Figure 16a illustrates the distance required for each type of V/STOL aircraft studied during terminal operations and the nearest occupied buildings which would be a part of the noise conscious community. The distances assume the aircraft will not exceed the outdoor comparative peak perceived noise level as determined by this study. A certain amount of scatter is indicated by the length of the cross-hatched portions at the end of each column. The scatter is defined in terms of distances based on a plus and minus five percent subjective scatter about the 50 percent midpoint determined in this study and referred to as the comparative peak PNdb. Similarly, Figure 16b applies to the altitudes which the aircraft must maintain in cruise above populated buildings so as not to exceed the comparative peak PNdb. It should be noted that the distances and altitudes are illustrative of the restrictions which may be imposed on aircraft operations if no energetic efforts are made to reduce the acoustical noise levels emanating from the aircraft.

Critical analyses of the noises produced by propulsion system components, and the anticipated practical aircraft operational requirements, yield the noise reduction required to meet public noise exposure criteria (see Figure 17). These criteria are based on an annoyance comparable to that produced by current jet transports. Several components were revealed by this study to consistently require a great amount of noise level reduction or control: engine intakes and exhausts, fans, propellers, and helicopter rotors. Designers of V/STOL aircraft must recognize and deal effectively with these major sources of noise in order to ensure their public acceptability.

Paired comparison testing is an effective means of eliciting subjective reaction to sounds of similar characteristics. The ease of scoring and the built-in checks for consistency of results aid in the evaluation and usefulness of the subjective test data and are amenable to mathematical analysis. The degree of success in predicting subjective public reaction to future V/STOL aircraft noise depends greatly on the quality and accuracy of the test sounds which are presented. The quality of the sounds, in turn, can only be as good as the analytical predictions. The acoustical characteristics of production aircraft will probably differ somewhat from those of the studied configurations, but will nevertheless be represented by the sounds used in this program.

Part a.

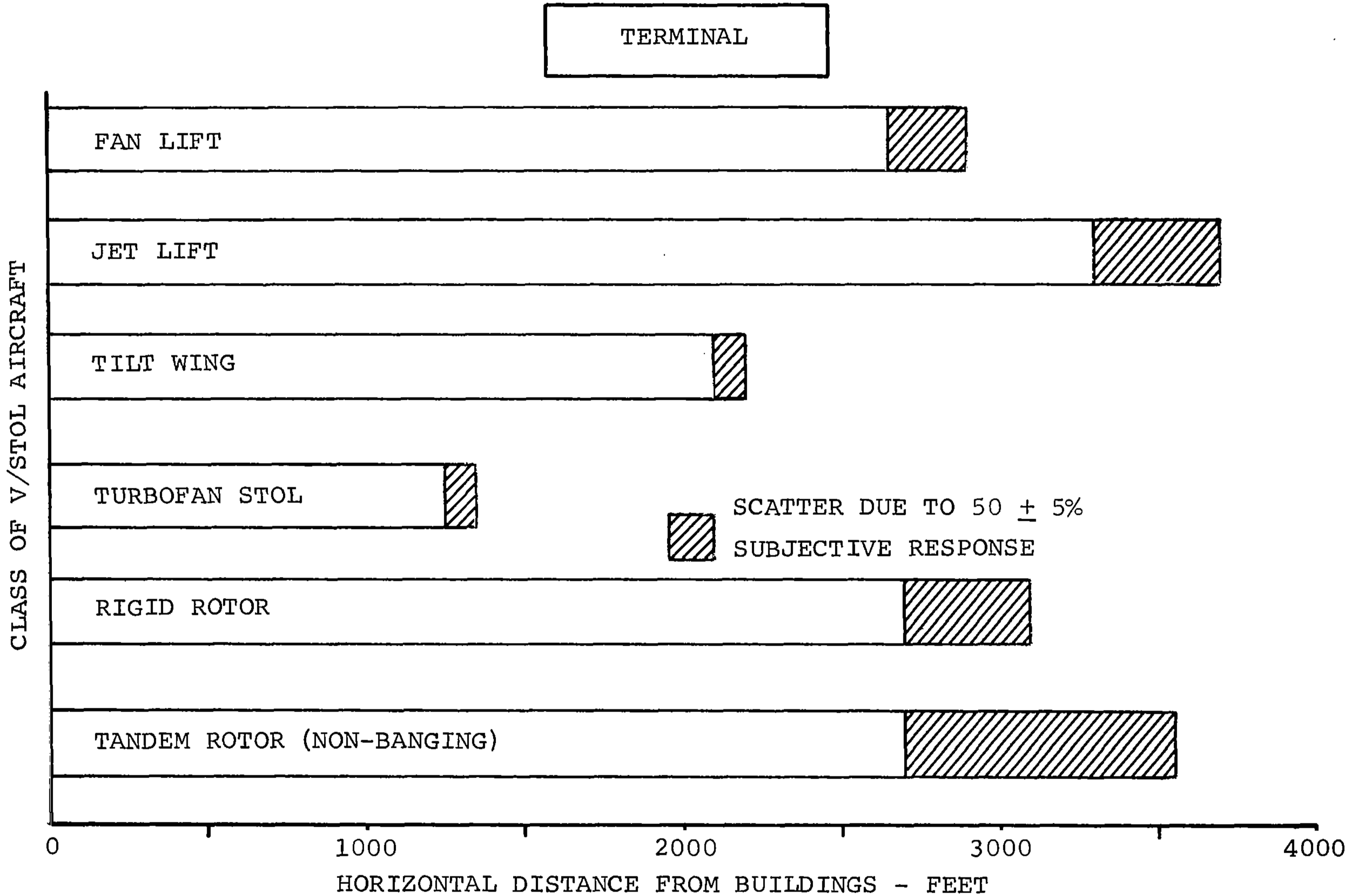


Figure 16. Required Distance and Altitude to Set Outdoor Comparative Peak Noise Level of Short-Haul V/STOL Aircraft if No Noise Reduction Techniques are Applied.

Part b.

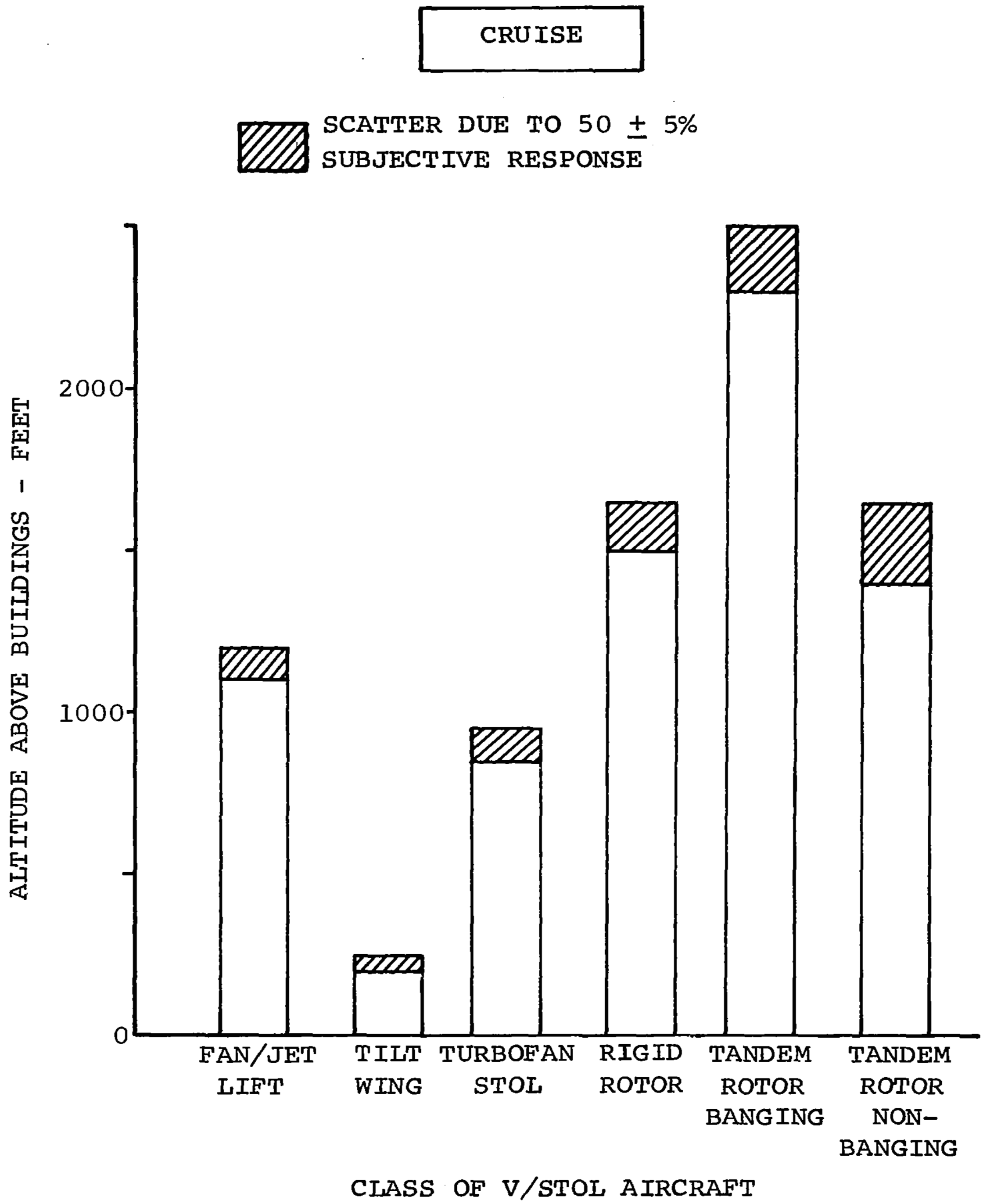


Figure 16. Concluded.

Part a.

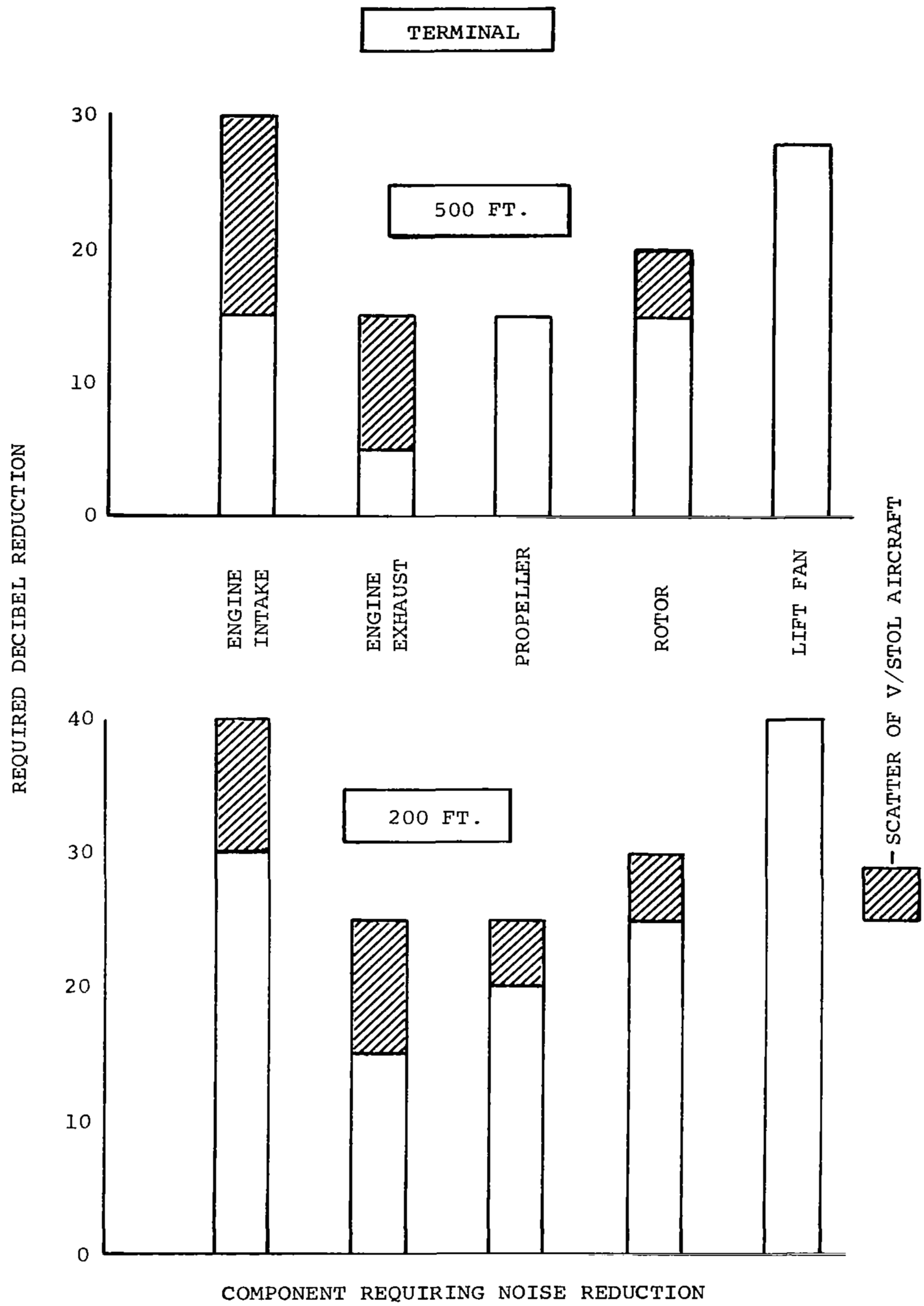


Figure 17. Terminal and Cruise Noise Reduction Required to Operate at Specified Distances and Altitudes Without Exceeding Comparative Peak Perceived Noise Level.

Part b.

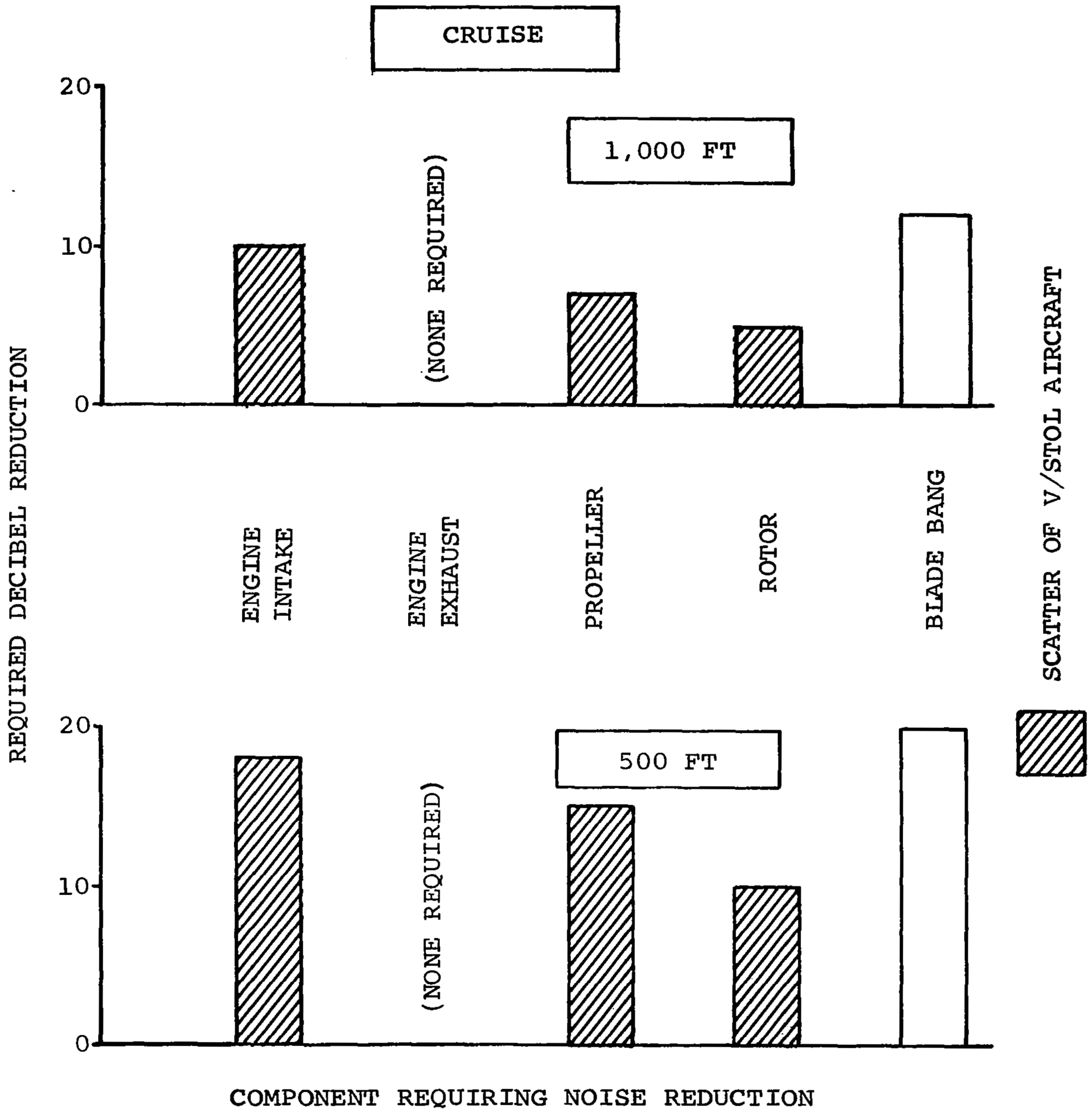


Figure 17. Concluded.

APPENDIX A

AIRCRAFT DESIGN ANALYSIS

The fan lift VTOL (Figure 18) employs two lifting fans in the wing driven by four independent gas generators to provide powered lift. The gas generators are mounted on top of the fuselage and their exhausts are cross-ducted to the fans for safety. Hover control is achieved through the use of bidirectional reaction control nozzles at the airplane extremeties. Air is supplied to the nozzles by turbocompressors which are driven by bleed air from the gas generator exhaust. In addition, the thrust of turbofan cruise engines is deflected downward at takeoff to provide added lift.

To achieve forward flight, more of the cruise engine thrust is deflected rearward. The resulting loss of vertical lift from the engines is off-set by the gain of wing aerodynamic lift as forward speed increases. When sufficient airspeed is attained to support the aircraft by conventional aerodynamic means, the lifting and hover control mechanisms are shut down with the aircraft proceeding as a conventional two-engine, fixed-wing turbofan vehicle.

The jet lift design (Figure 19) utilizes a relatively large number of engines for reasons of safety and control. Five lift turbofan engines are installed vertically in each of the pods mounted at the tips of the forward swept wing. These ten lift engines, together with the downward deflected thrust of the four turbofan cruise engines mounted at the aft end of the fuselage, provide VTOL lift and control. Conversion to forward flight is accomplished as with the fan lift concept. After sufficient forward airspeed is attained by cruise engine vectored exhaust thrust, the lift engines are shut down.

External and internal acoustical environments were a major design consideration for this concept. The lift engine by-pass ratio of 2.5 was a compromise between noise propagation and engine size and weight. The wing tip location was chosen to give low internal noise levels, eliminate unfavorable interactions of the propulsion and airframe aerodynamics, and give control without a separate reaction control system. These advantages were felt to be more important than the wing weight and low roll inertia inherent in a fuselage mounted design.

APPENDIX A

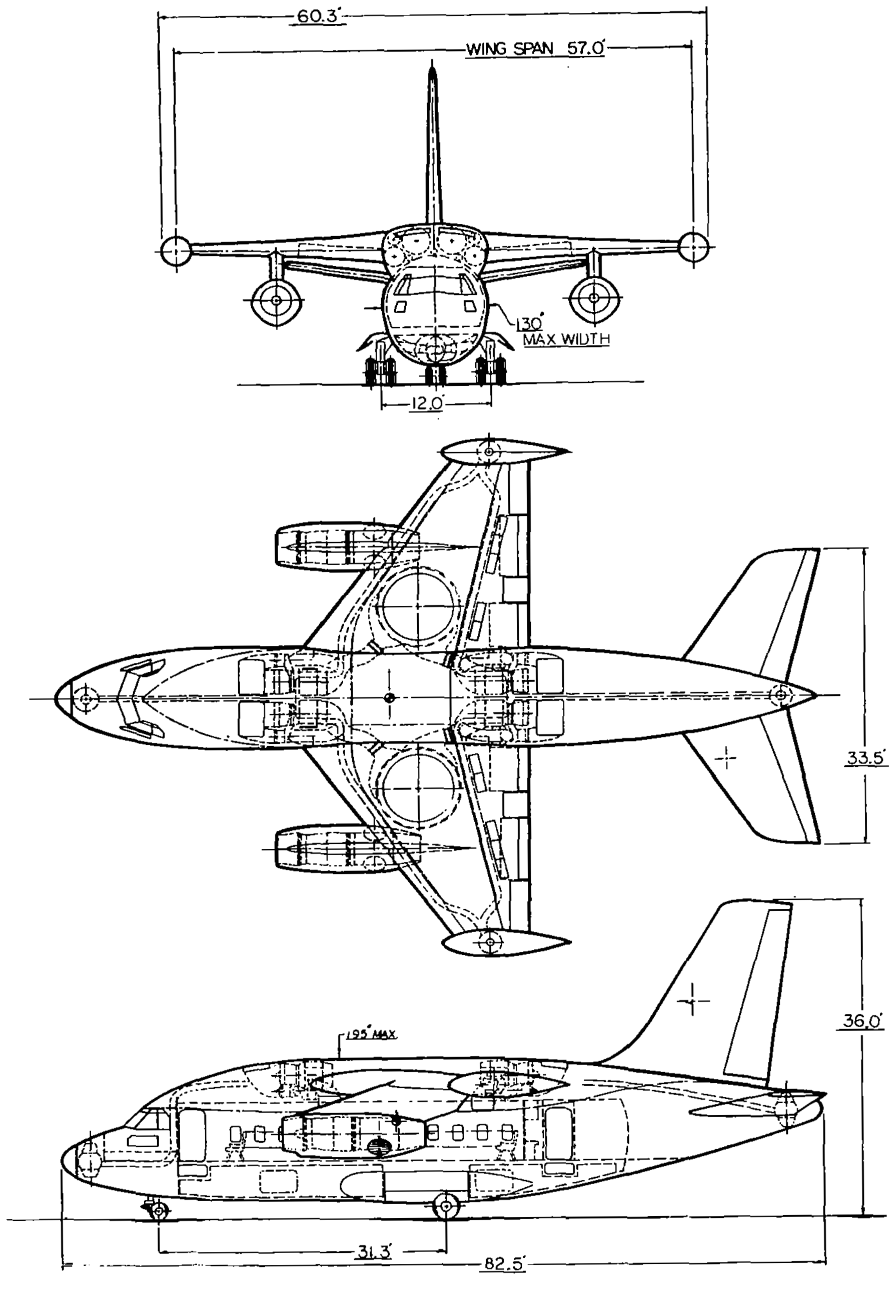


Figure 18. Fan Lift Configuration.

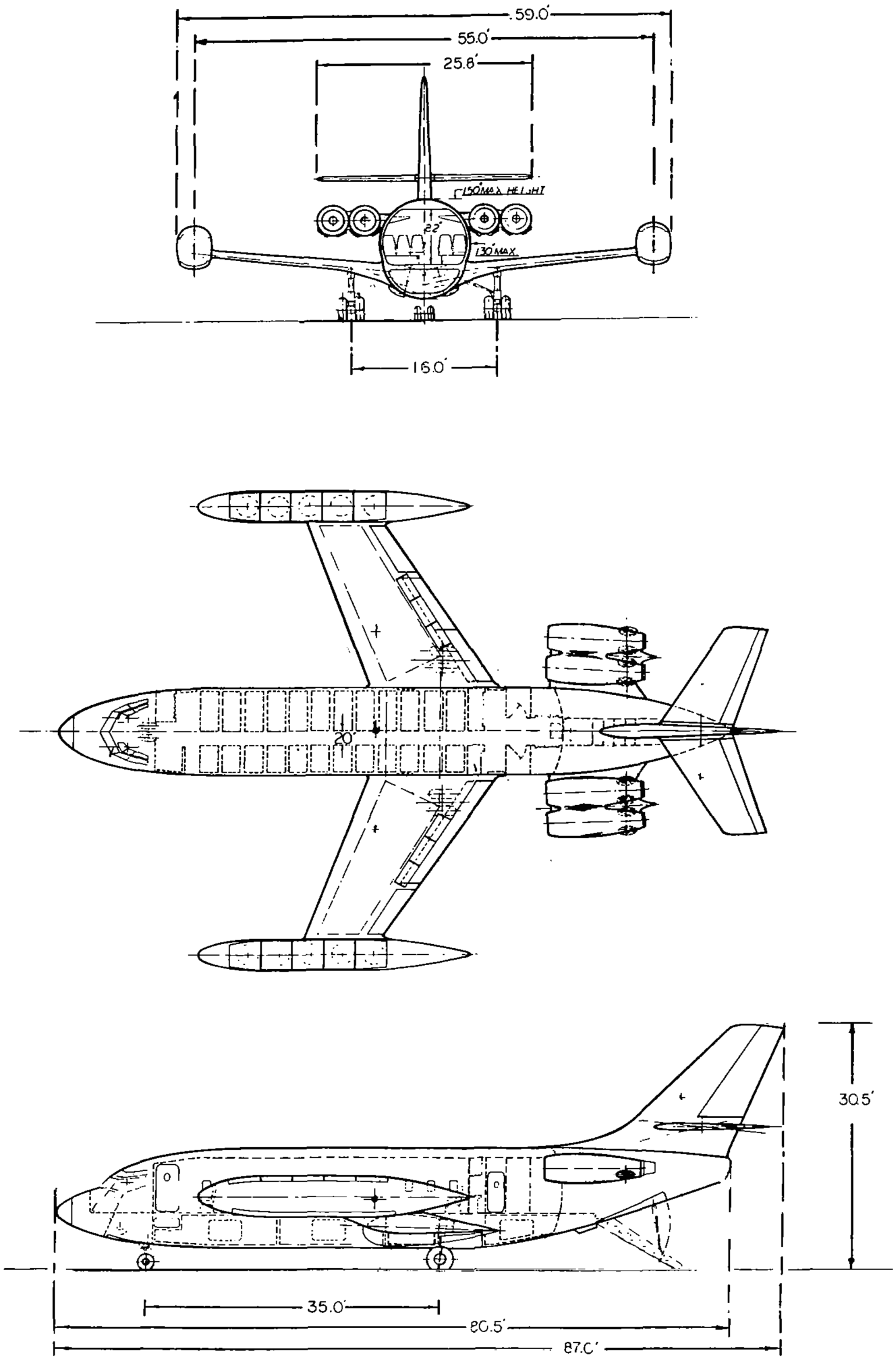


Figure 19. Jet Lift Configuration.

APPENDIX A

The tilt wing VTOL aircraft (Figure 20) has four propellers and four turboshaft engines which are coupled by interconnecting shafting. One of the features desirable from the noise view point is the absence of the tail rotor normally used to provide pitch control. This is accomplished by monocyclic (single-axis-cyclic) control of the propellers. The relatively low tip speed of 850 feet per second also contributes to a favorable acoustical environment.

In cruise the vertically-oriented, wing-mounted engines and the propellers are tilted forward along with the wing. Since the propellers are designed for a high figure of merit in hover, the blade tip speed in low altitude cruise is lowered to 500 feet per second, which is another good noise feature.

While the concepts described so far are designed for VTOL operation, they could, in an emergency or overload condition, be operated in the STOL mode. The turbofan aircraft of this study, however, is a pure STOL configuration (Figure 21) which obtains its short field capability by use of a powerful high lift wing flap system rather than by the installation of extra lift devices to provide vertical lift. Exhaust gas from the cruise engines is directed over the doubleslotted trailing edge flaps to provide boundary layer control and thrust redirection. Other than these features, the airplane is very conventional in appearance and operation.

The rigid rotor VTOL aircraft (Figure 22) has a single three-bladed main rotor and an antitorque tail rotor for VTOL operation. In cruise the rotor is unloaded by the aerodynamic action of the wings, folded, and stowed into the top section of the fuselage. Forward thrust is then provided by two conventional propellers mounted on the wings. The propulsion system consists of four turboshaft engines driving the rotors and propellers through individual overrunning clutches. Maximum rotor and propeller tip speeds are 800 and 900 feet per second, respectively. The rigid rotor principle with free gyro control phasing into aerodynamic control as rpm is reduced permits stopping of the blades in flight during transition.

The tandem rotor VTOL (Figure 23) is a triple-turbine powered helicopter design with four blades on each rotor. VTOL operation and control is achieved by mechanically articulated rotors, which, for cruise operation, are tilted slightly forward in the direction of flight. Differential cyclic pitch of the rotors is used for longitudinal attitude control, lateral

APPENDIX A

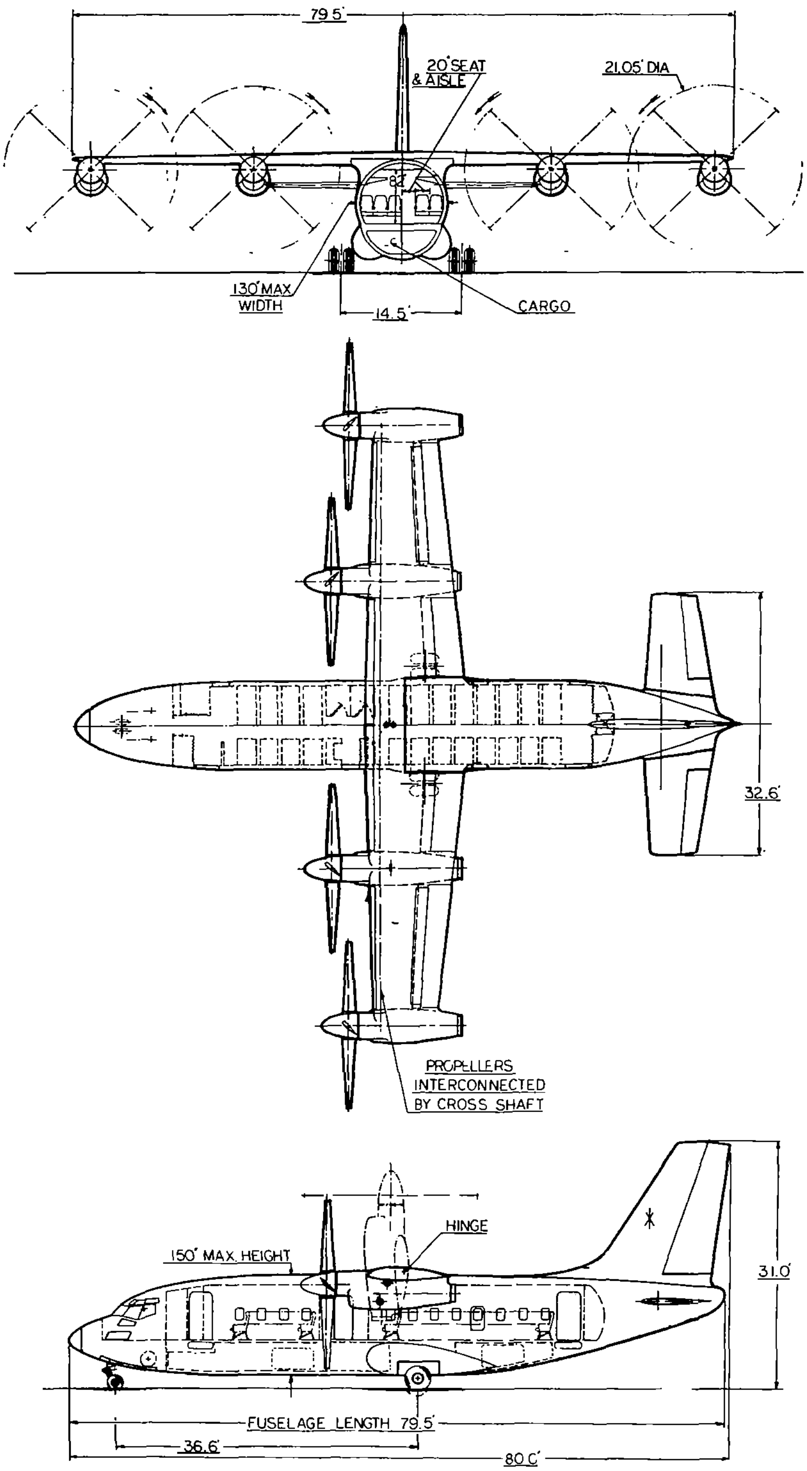


Figure 20. Tilt Wing Configuration.

APPENDIX A

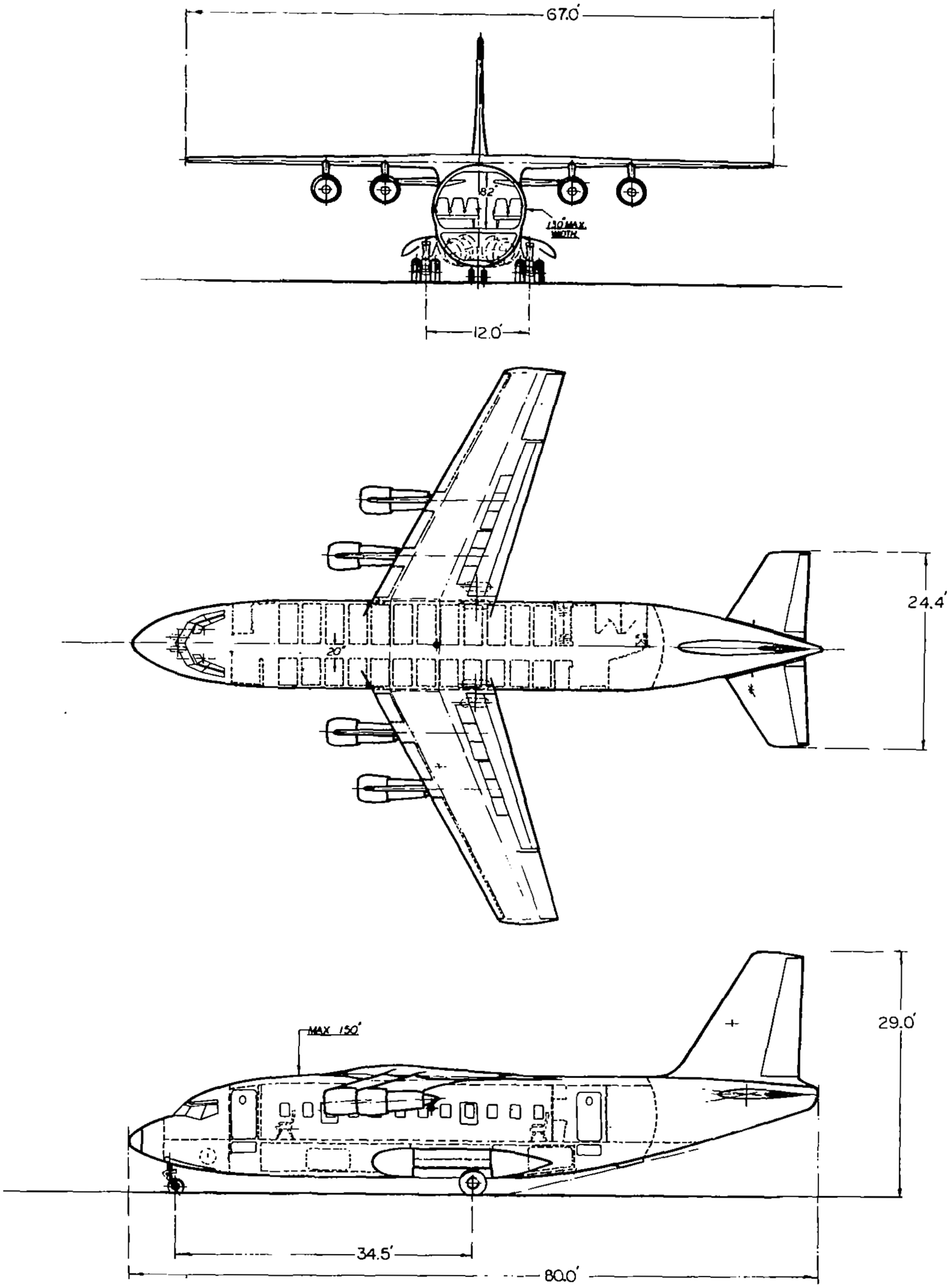


Figure 21. Turbofan STOL Configuration.

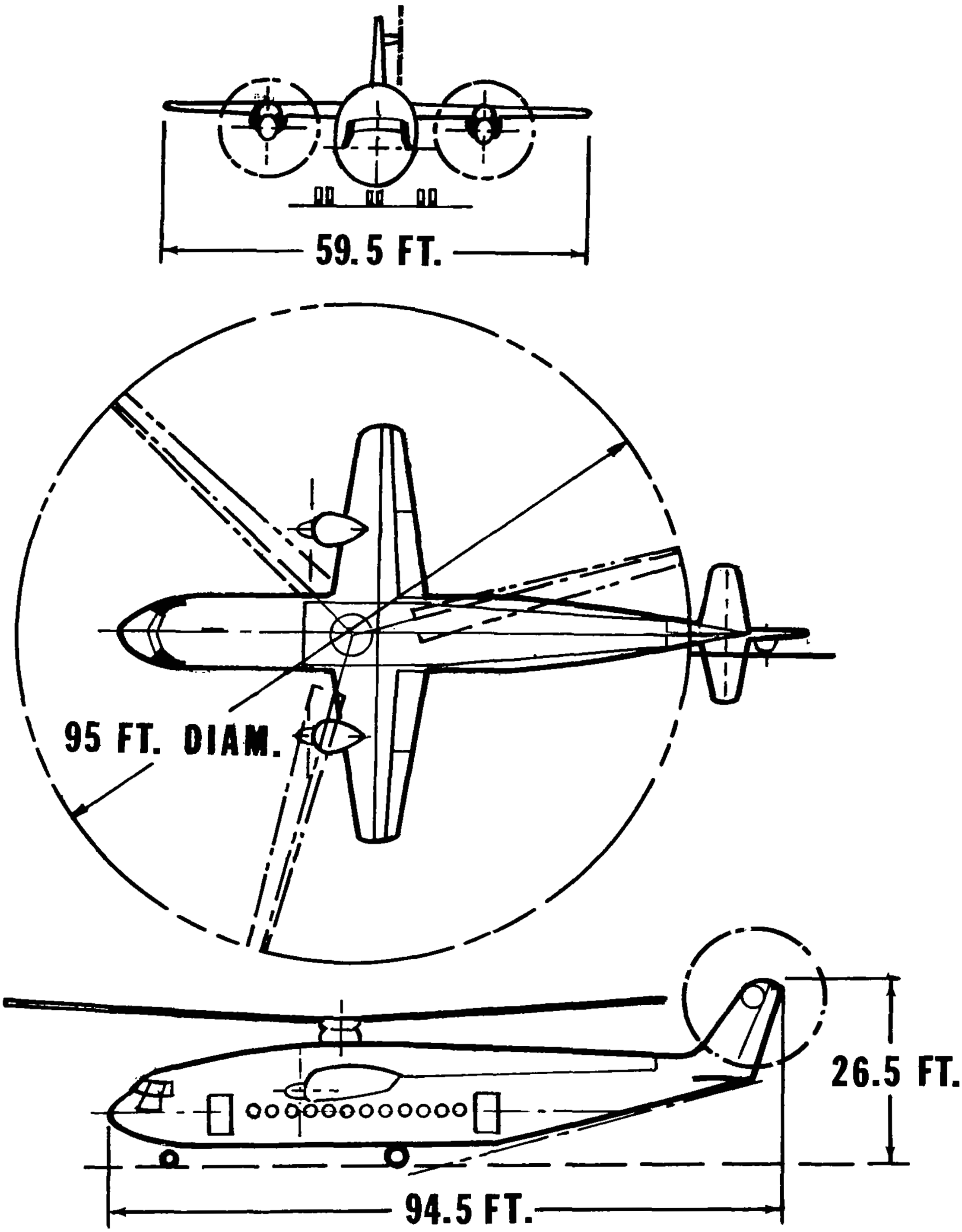


Figure 22. Rigid Rotor Configuration.

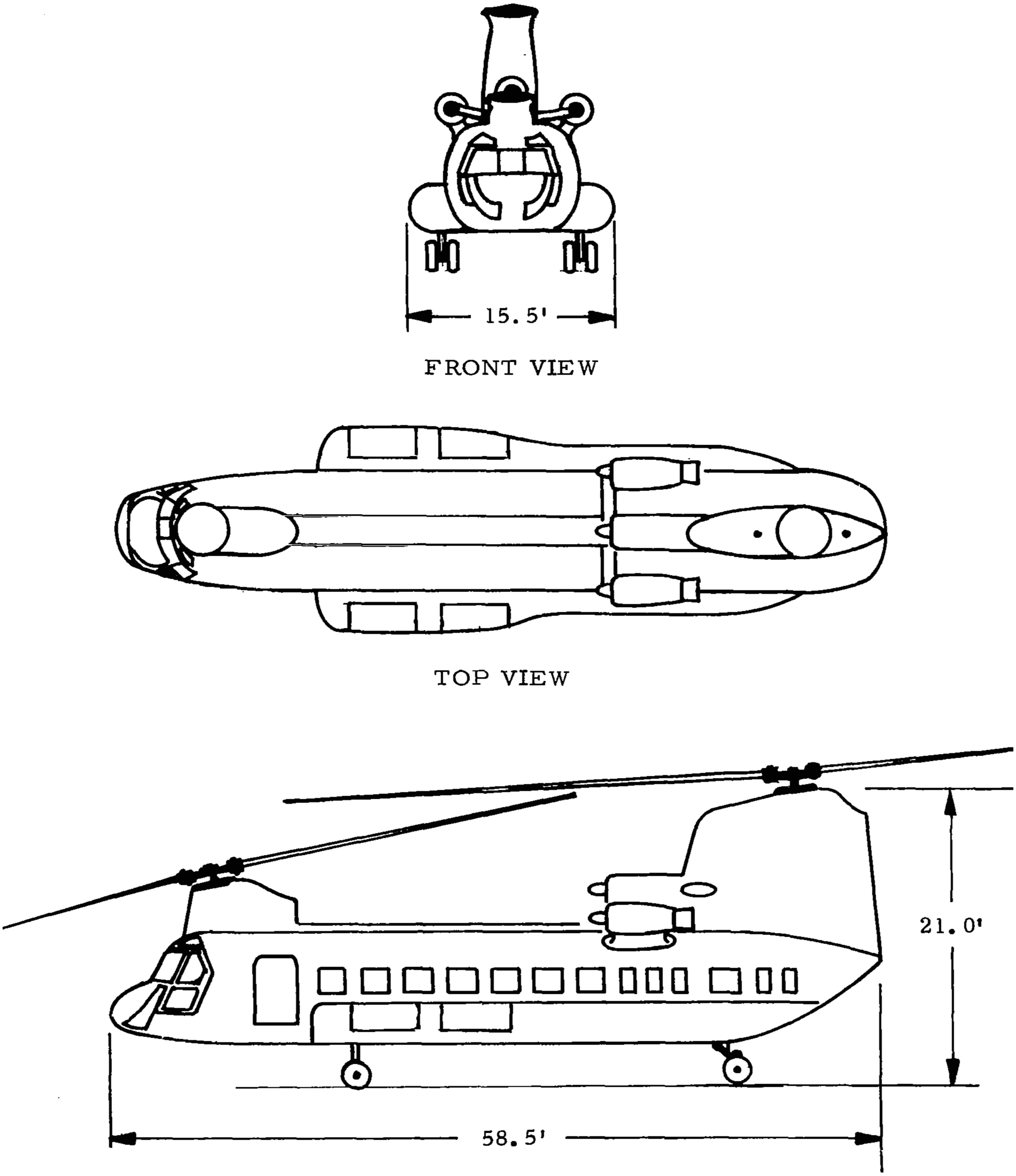


Figure 23. Tandem Rotor Configuration.

cyclic for roll control, and differential lateral cyclic for yaw control.

Table II lists the major design parameters for each of the aircraft described above.

Noise Analysis

Octave-band sound pressure levels for each of the aircraft were predicted for the takeoff and cruise mode. Because of the dissimilarity in propulsive mechanisms each aircraft employs in takeoff as opposed to level cruise flight, the resulting acoustical signatures may be strikingly different in the two operating regimes even for the same aircraft.

Octave band noise spectra initially are predicted for an observer's post 500 feet away from the takeoff point when the aircraft is in the VTOL (STOL) mode (Figure 24), and for another point 2000 feet below the flight path when the aircraft is in the cruise configuration (Figure 25). The lines on Figures 24 and 25 represent the envelopes of the maximum levels expected during a complete transient noise condition (such as a fly-over or takeoff) with respect to an observer. The spectrum shown does not necessarily occur at any one instant of time; rather, the levels in the individual octave bands may vary in relation to each other somewhat, but will not be higher than indicated on the charts.

To simulate the acoustical signature of a proposed aircraft configuration in believable and subjectively convincing detail, including spectral content, time-amplitude variation, and Doppler shift, detailed analysis of noise properties had to be conducted. The following descriptions illustrate the methods used to derive the detailed acoustical signatures.

Fan lift VTOL. - To determine terminal noise (Figure 26), the gas generator intake noise was predicted according to reference 5. The spectrum of control nozzle exhaust was predicted according to references 6 and 7, assuming that the broad band noise produced followed the acoustical behavior of a jet based on flow velocity and geometry. Cruise engine intake noise was predicted by the same method as for the gas generator intake noise, reference 6. Cruise engine exhaust noises in hover were calculated according to references 6 and 7, taking proper account of the geometry of the deflected

APPENDIX A

TABLE II

GENERAL AIRCRAFT CHARACTERISTICS

Nomenclature	Units	Data					
Aircraft		Fan Lift VTOL	Jet Lift VTOL	Tilt Wing VTOL	Turbo-Fan STOL	Rigid Rotor VTOL	Tandem Rotor VTOL
Reference Figure	-	18	19	20	21	22	23
Gross Weight	lb	85 972	80 758	71 704	62 824	71 000	46 305
Surface Areas							
Wing	sq ft	1 025	712	787	749	591	-
Horizontal Tail	sq ft	335	186	238	180	158	-
Vertical Tail	sq ft	253	177	178	146	203	276
Overall Dimensions							
Length	ft	82.5	80.5	79.5	80.0	94.5	58.5
Width	ft	60.3	59.0	79.5	67.0	57.5	15.5
Height	ft	36.0	30.5	31.0	29.0	26.5	21.0
Cruise Power Plant							
Number	-	2	4	4	4	4	3
Type	-	Turbofan	Turbofan	Turboshaft	Turbofan	Turboshaft	Turboshaft
Maximum Thrust	lb	14 900	6 950	-	7 500	-	-
Maximum Power	hp	-	-	6 740	-	4 105	3 750
By-pass Ratio	-	3	3	-	3	-	-
Pressure Ratio	-	20	16	14	20	13	9
T_4	°R	2 600	2 600	2 600	2 600	2 600	2 300
Lift Power Plant				-	-	-	-
Number	-	2 Fans, 4 G.G.[1]	10				
Type	-	-	Turbofan				
Maximum Thrust	lb	38 200 (Fan)	9 970				
Maximum Power	hp	-	-				
By-pass Ratio	-	8 (Fan)	2.5				
Pressure Ratio	-	12 (Gen.)	7				
T_4	°R	2 600	2 360				
Main Rotor		-	-	-	-		
Number	-					1	2
Diameter	ft					95.0	60.0
Number of Blades	-					3	4
Solidity	-					.055	.090
Maximum Tip Speed	fps					800	710
Tail Rotor		-	-	-	-		-
Number	-					1	
Diameter	ft					20.0	
Number of Blades	-					4	
Solidity	-					0.12	
Maximum Tip Speed	fps					800	
Propeller		-	-		-		-
Number	-			4		2	
Diameter	ft			21.05		13.5	
Number of Blades	-			4		4	
Solidity	-			.25		0.12	
Maximum Tip Speed	fps			850 (Cruise) 500 (Terminal)		900	

[1]Gas generators.

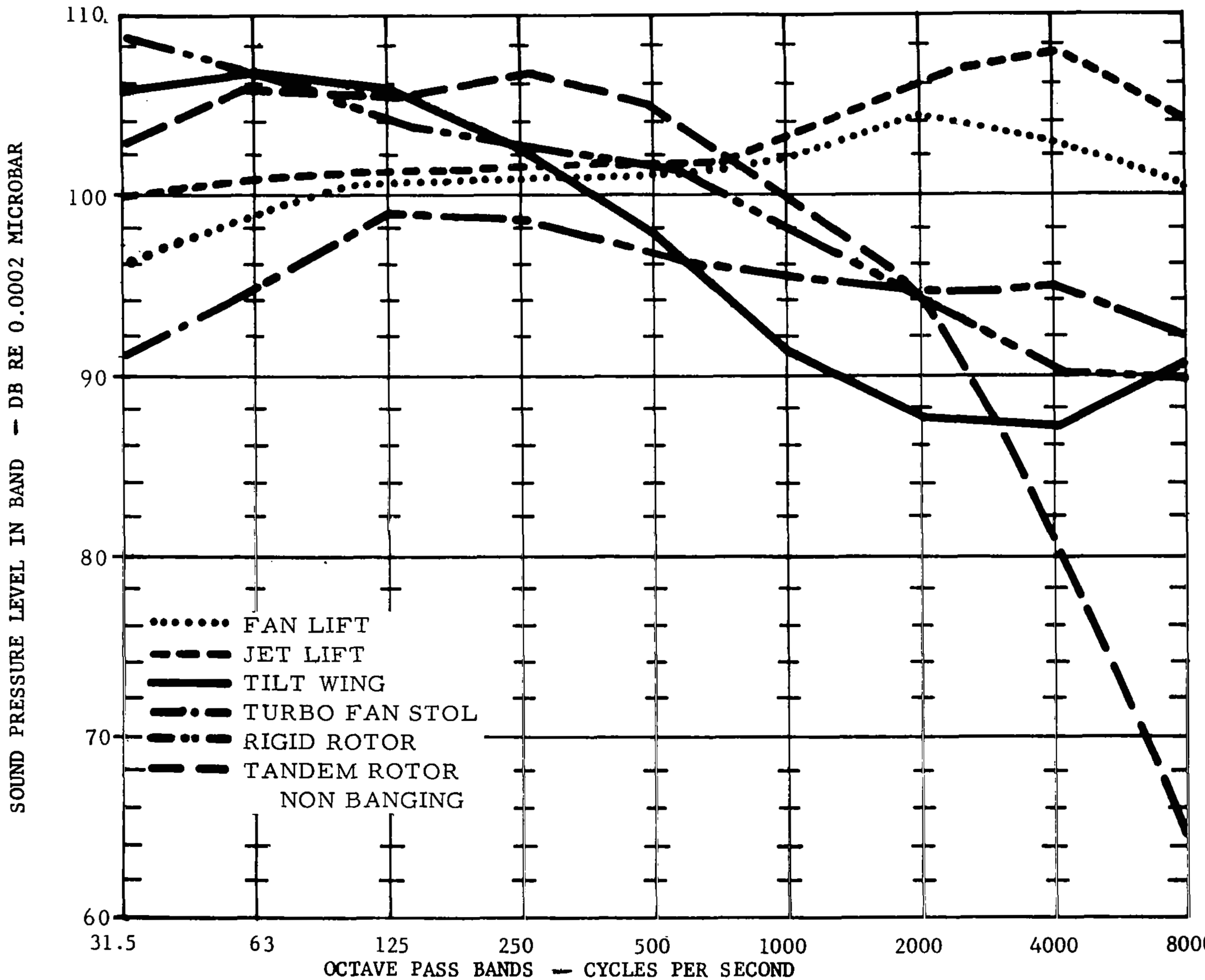


Figure 24. Octave Band Noise Spectra at 500 Feet During VTOL (STOL) Mode.

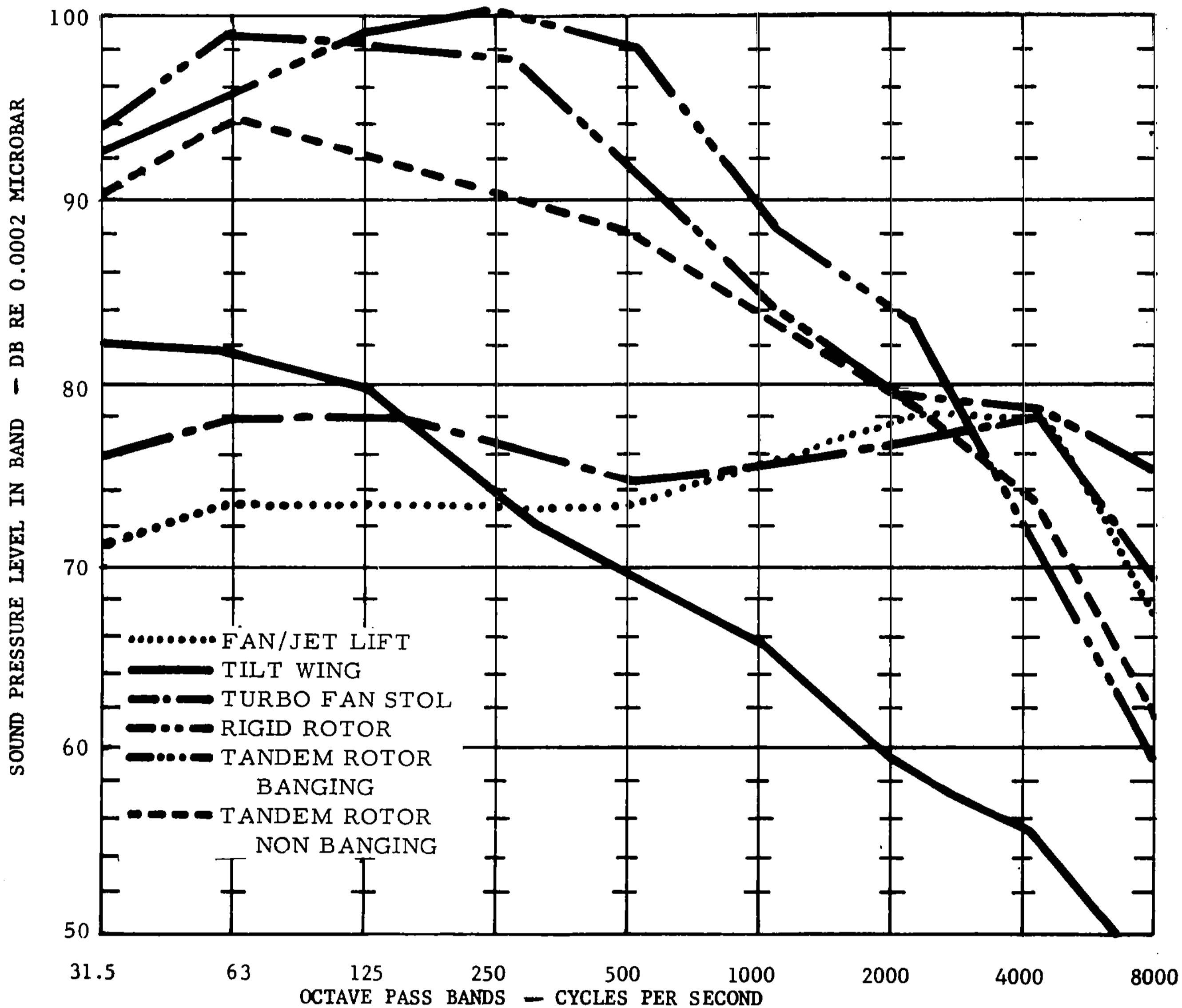


Figure 25. Octave Band Noise Spectra at 2000 Feet During Cruise Mode.

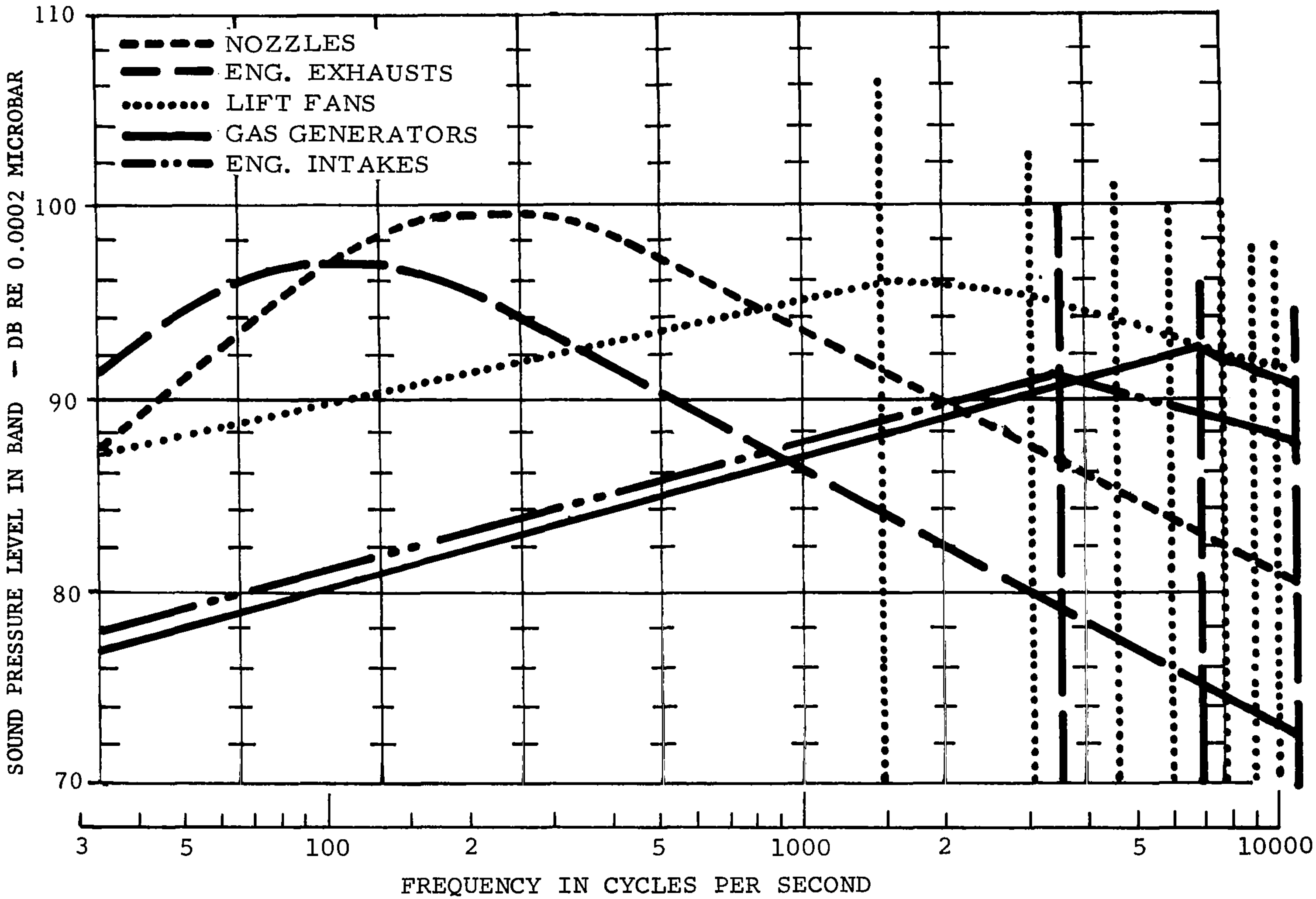


Figure 26. Fan Lift Terminal Spectrum.

exhausts. The noise of the wing-mounted lifting fans was predicted according to a method developed in reference 8.

In cruise, there are considerably fewer noise sources than at takeoff. Both engines emit high-frequency inlet noise (reference 5) and low frequency broad band jet primary and by-pass exhaust noises (references 6 and 7). Figure 28 shows slightly different frequencies, which is explained in the discussion following the description of the jet lift VTOL spectrum for cruise.

Jet lift VTOL. - In terminal noise associated with the jet lift VTOL (Figure 27), the lift engine intake noise consists of pure tones (reference 5). The primary and by-pass exhausts (by-pass ratio: 2.5) are centered on 106 and 41 Hz, respectively (references 6 and 7). The cruise engines, also used in the terminal operation, emit high frequency tones from the inlet (reference 5), and broad band jet exhaust noise (references 6 and 7) from the deflected exhausts.

In cruise (Figure 28), the four cruise engines produce inlet noise frequencies (reference 5). Primary exhaust noise is broad band in character; by-pass exhaust noise, somewhat less noisy and lower in frequency, is centered around 40 Hz (references 6 and 7).

The rationale for selecting only one spectrum to represent both fan lift and jet lift VTOL noises in cruise was as follows. Both aircraft are propelled by by-pass cruise engines emitting inlet-, primary- and by-pass exhaust noises. Even though the engines are located under the wings on the fan lift and at the rear of the fuselage on the jet lift, this difference in physical location results in a negligible acoustical change in the radiation field with respect to an acoustical observer 2000 feet below the flight path if it is assumed that the aft mounted jets are reasonably far apart. Furthermore, even though the fan lift has two larger engines compared to the jet lift's four smaller ones, the envelope of their octave band spectra were similar to within two decibels in most cases. As for the slight differences in frequency spectrum location of the maxima of the primary jet noises, this difference is negligible as far as perceived noise calculations are concerned. The same holds for the fundamental tones of the inlet noises on both aircraft; although these tones are located in the most sensitive region of the frequency spectrum as far as human auditory response is concerned, the difference between them is

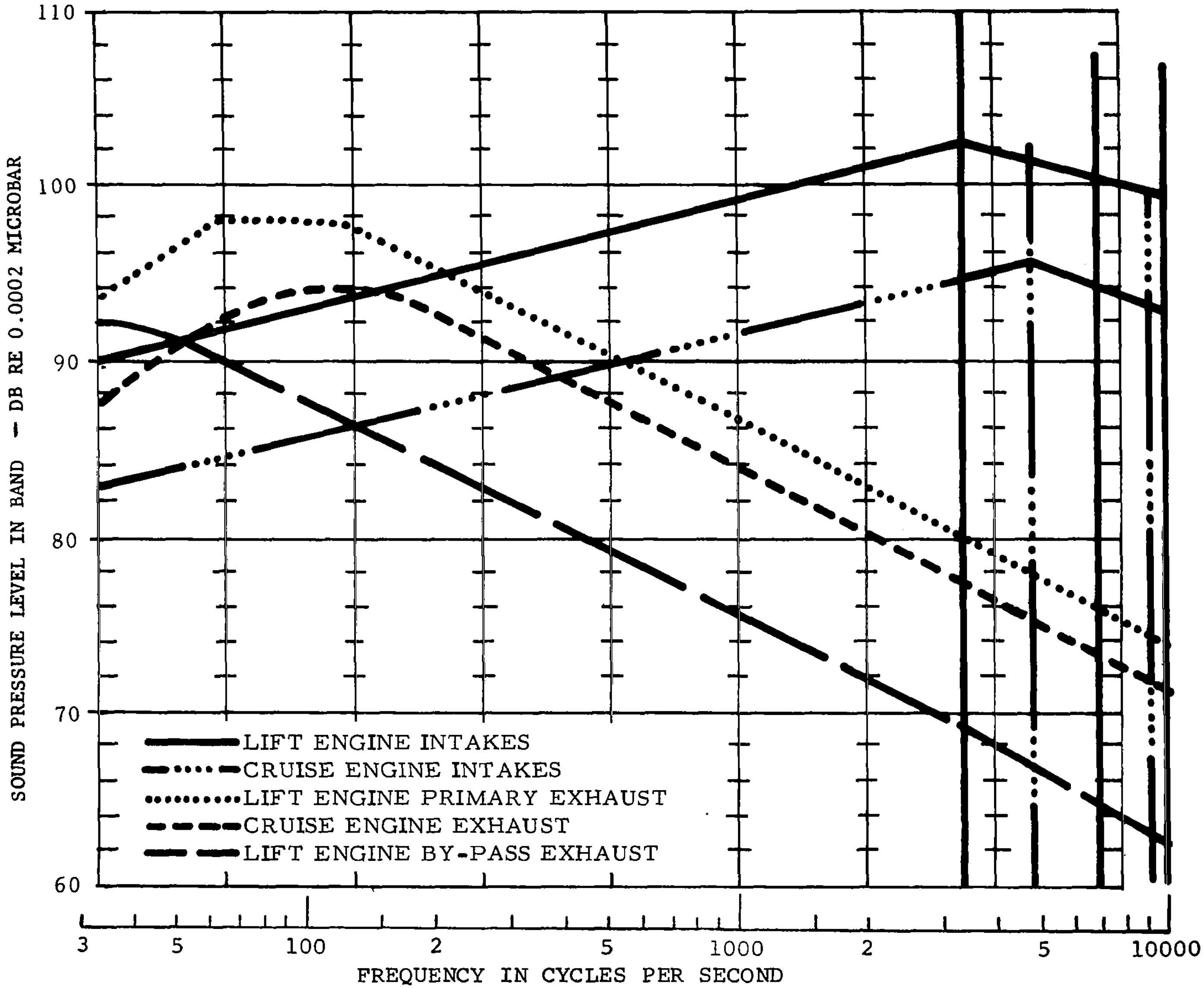


Figure 27. Jet Lift Terminal Spectrum.

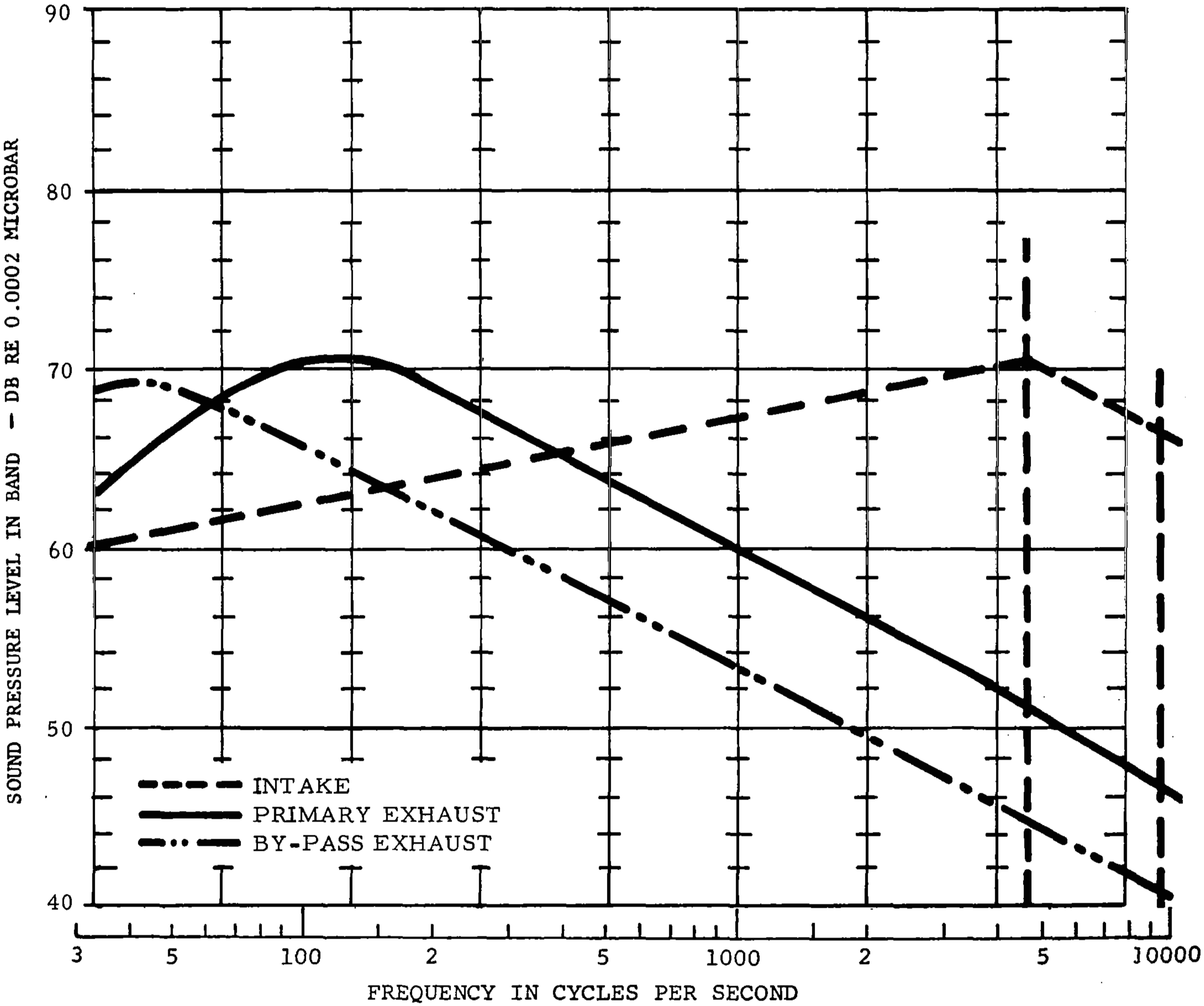


Figure 28. Fan Lift or Jet Lift Spectrum in Cruise.

small enough to evoke the same response, according to the flat portion of the curve representing equal annoyance as a function of frequency in reference 9.

Tilt wing VTOL. - The primary terminal noise sources on the tilt wing (Figure 29) are the propellers, whose acoustical characteristics were calculated according to references 10 and 11. The blade passage frequency determines the fundamental frequency, with subsequent harmonics at 50 Hz intervals. Only three harmonics are indicated in Figure 29, with the line above them outlining the approximate envelope of higher harmonics. Blade vortex noise is broad band in character and similar to jet exhaust noise in spectrum shape. The intake noise of the gas turbines is represented by a pure tone and some broad band noise.

In the cruise condition (Figure 30), all noise frequencies of importance to an acoustical observer in the far field are different from those predicted for the terminal condition except for turbine whine. This is due to the reduction in propeller blade tip speed from 850 feet per second to 500 feet per second, thereby placing the fundamental blade rotational frequency at 30 Hz with upper harmonics at intervals of 30 Hz. The peak of the blade vortex noise has likewise been shifted downward. The whine of the gas turbine, which is operated at the optimum rpm during all flight modes, has changed only slightly.

Turbofan STOL. - Predicted terminal noise for the turbofan STOL is presented in Figure 31. The turbofan intake noise was predicted to have pure tones (reference 5). Turbofan primary and by-pass exhausts, calculated according to references 6 and 7, resulted in spectrum peaks being located at 220 and 94 Hz respectively.

Since there is change in neither the type of powerplants nor the number of noise producing components, the cruise noise produced by the turbofan STOL is almost identical to its terminal noise (see Figure 32). However, as will be shown later, the amplitude-time history of these two acoustic events is sufficiently different to warrant investigation of each subjectively. Inlet noise in cruise has pure tones at 4400 and 8800 Hz, with primary engine exhaust noise centered on 86 Hz, and by-pass exhaust noise on 83 Hz.

Rigid rotor VTOL. - The predicted terminal noise for the

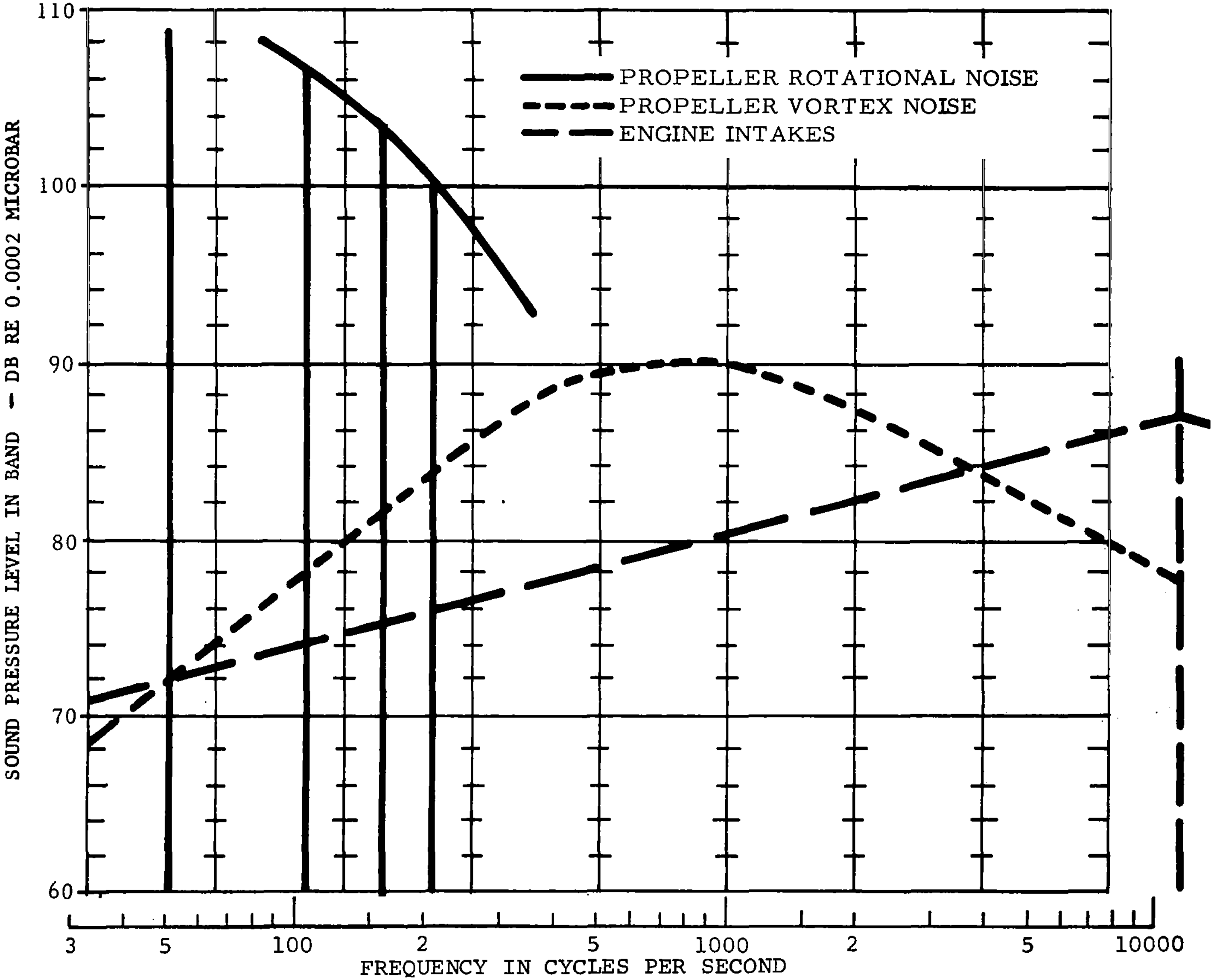


Figure 29. Tilt Wing Terminal Spectrum.

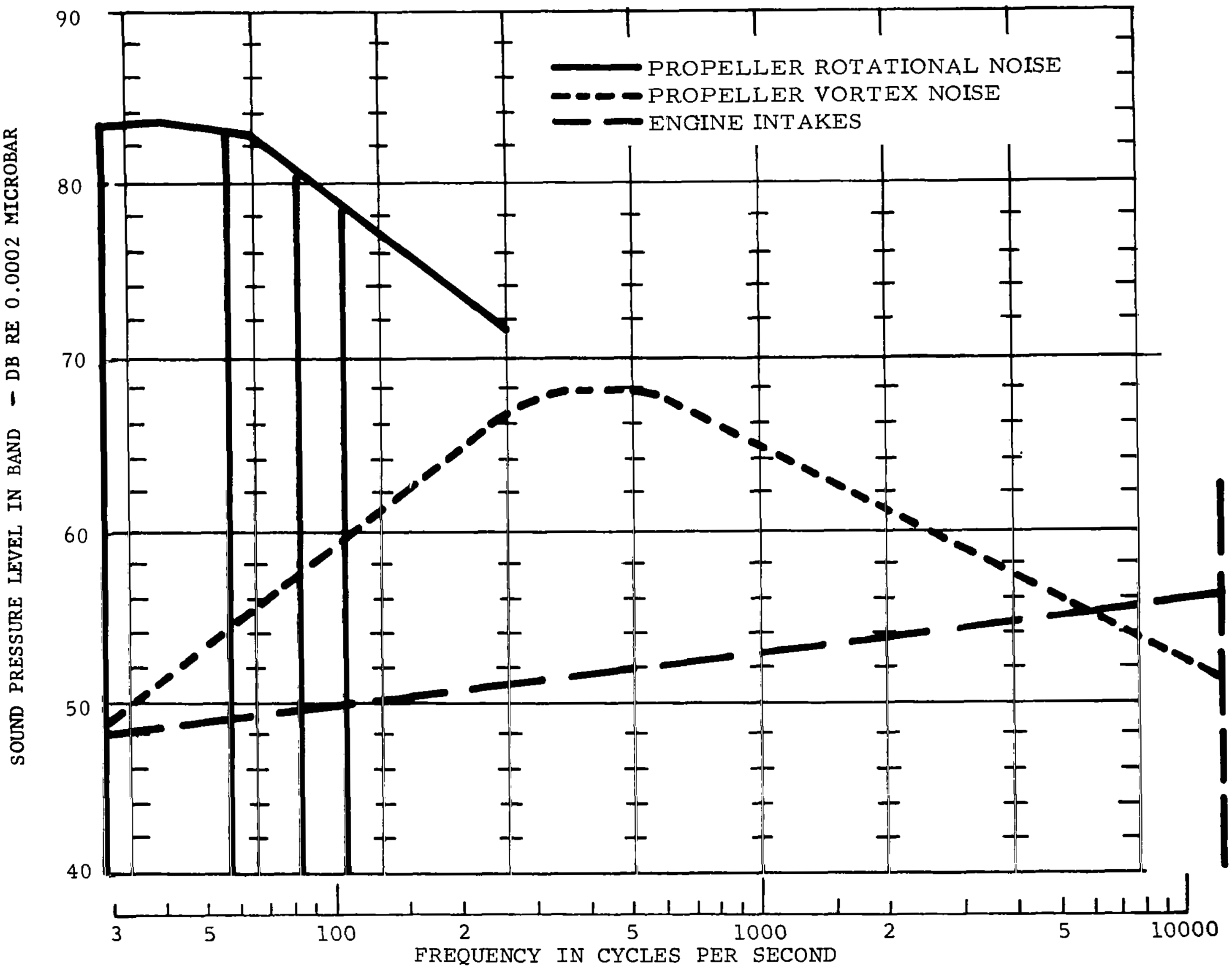


Figure 30. Tilt Wing Cruise Spectrum.

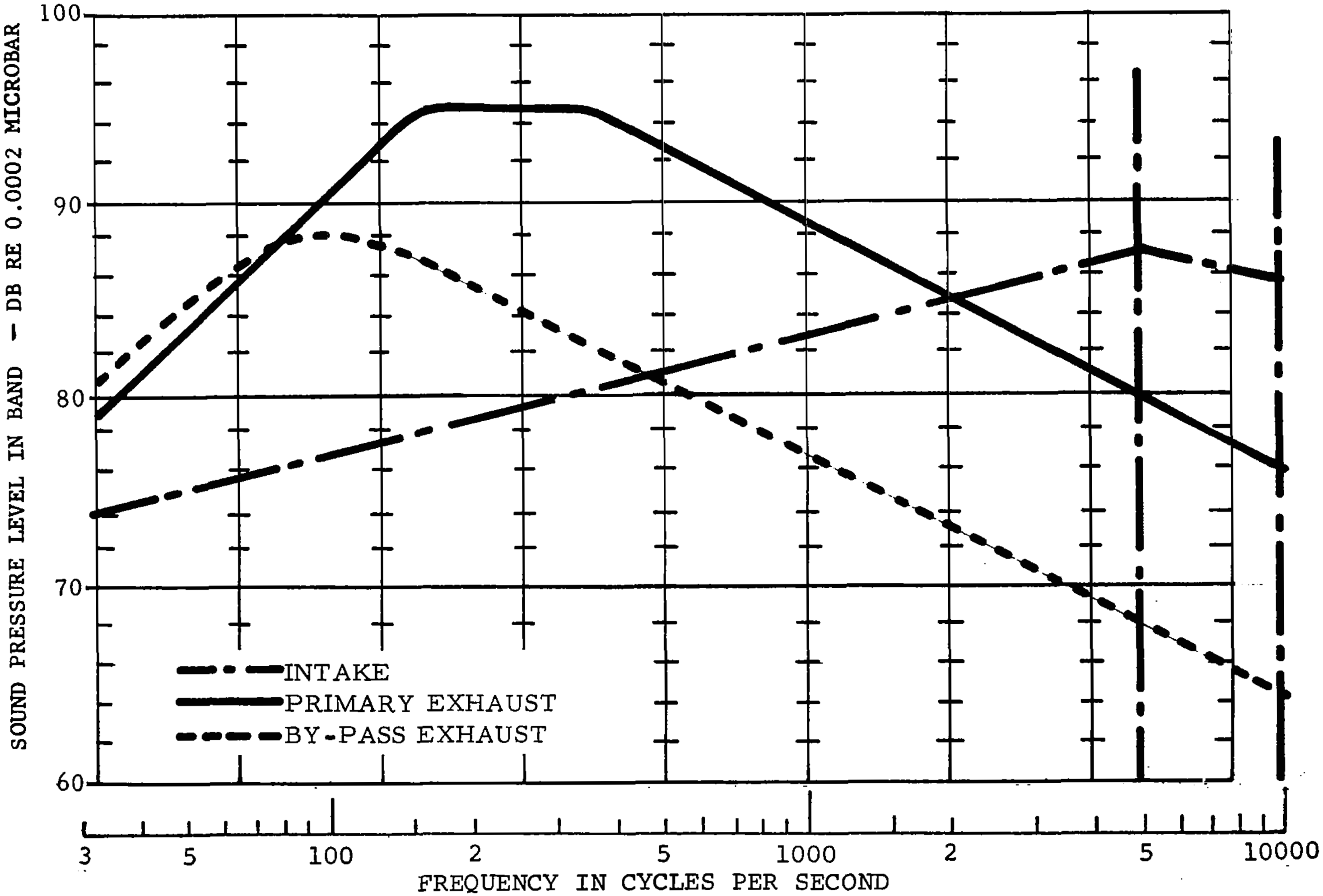


Figure 31. Turbofan STOL Terminal Spectrum.

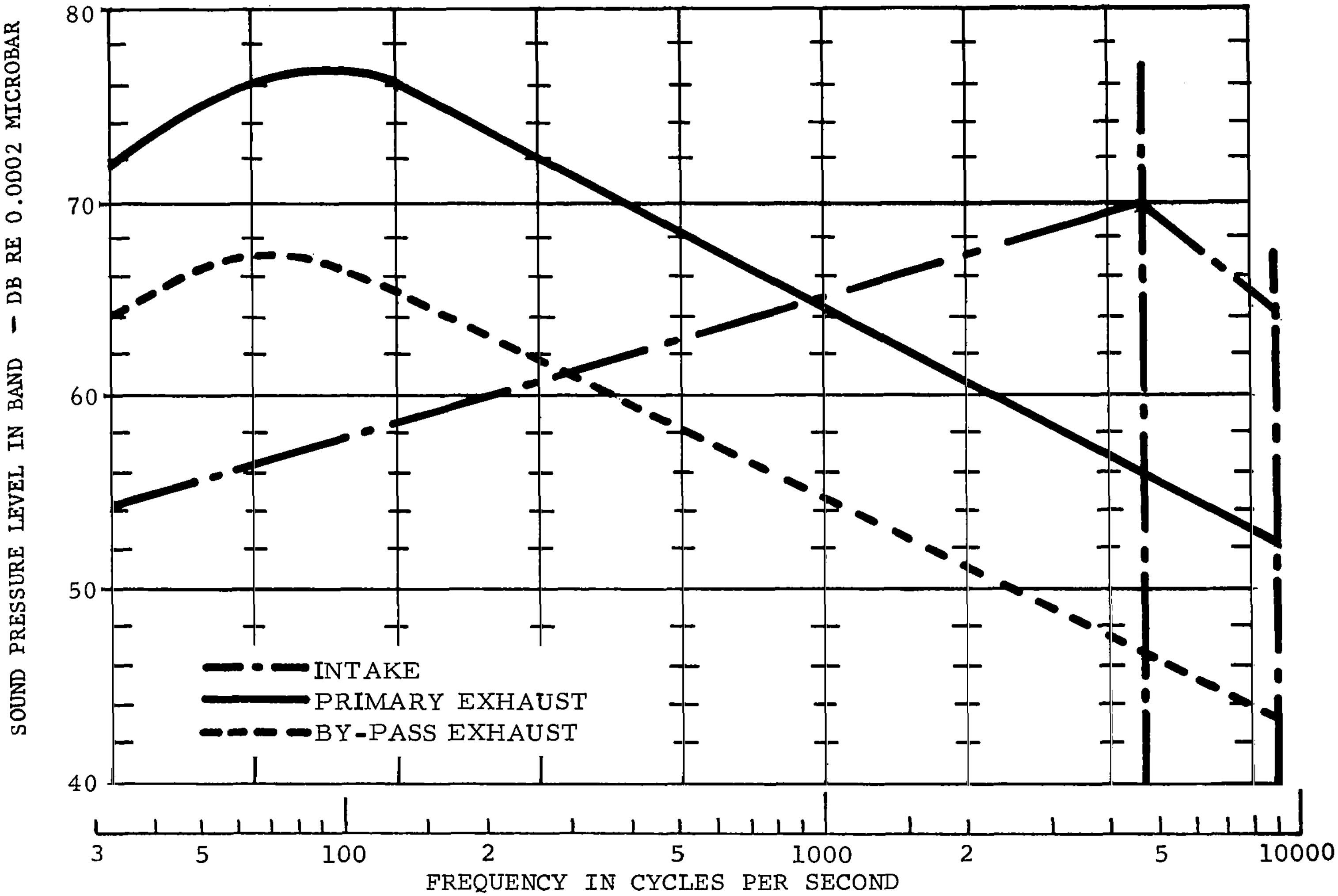


Figure 32. Turbofan STOL Cruise Spectrum.

rigid rotor VTOL is given in Figure 33. Main rotor and tail rotor fundamental rotational noise frequencies are determined by the blade passage frequency of each with respect to an acoustical observer. The approximate amplitude and frequency distribution of rotor rotational and vortex noises was derived by reference 11 based on propeller noise theory, and subsequently modified to fit the more realistic spectral distribution of large single rotor helicopters. Propeller noise and state-of-the-art rotor noise prediction methods (references 12 through 15) are unable to account for the amplitude distribution of rotational noise of harmonic orders higher than three. Therefore, modified in-house data on Sikorsky S-61N and S-64 helicopters were used to predict spectrum shapes of this large single rotor design.

The rigid rotor helicopter is converted to a conventional two propeller aircraft in cruise. Consequently, the propeller noise prediction methods of references 10 and 11 were used to predict the acoustical characteristics given in Figure 34.

Tandem rotor VTOL. - Figure 35 presents predicted terminal noise for the tandem rotor VTOL. Tandem rotor helicopter noise differs from single rotor helicopter noise primarily because of the absence of the tail rotor on the former. As with single rotor helicopter noise, no comprehensive noise prediction method exists at present for tandem rotor noise. Fundamental rotational noise frequencies occur at intervals of 17 Hz. Blade vortex noise is predicted to peak at approximately 500 Hz but is, however, far below the levels set by the main rotor rotational noise. Existing Boeing helicopter data on the 107 Model II commercial airline helicopter and the military CH-47 tandem rotor types have been used to predict the acoustical noise signature of a tandem rotor helicopter. Adjustments in spectrum were made on the basis of increased power, gross weight, blade radius, and the number of blades per rotor.

There is no change in configuration of the tandem rotor VTOL whether in takeoff or in cruise. Consequently, the cruise noise spectrum is practically identical with that at takeoff, except for the reduced noise level due to the increased distance from the observer and the change in amplitude-time history of the sound (see Figure 36).

Some present day helicopters have a rotor noise signature which includes the acoustical phenomenon described as blade-bang. It was decided to supplement the usefulness of this

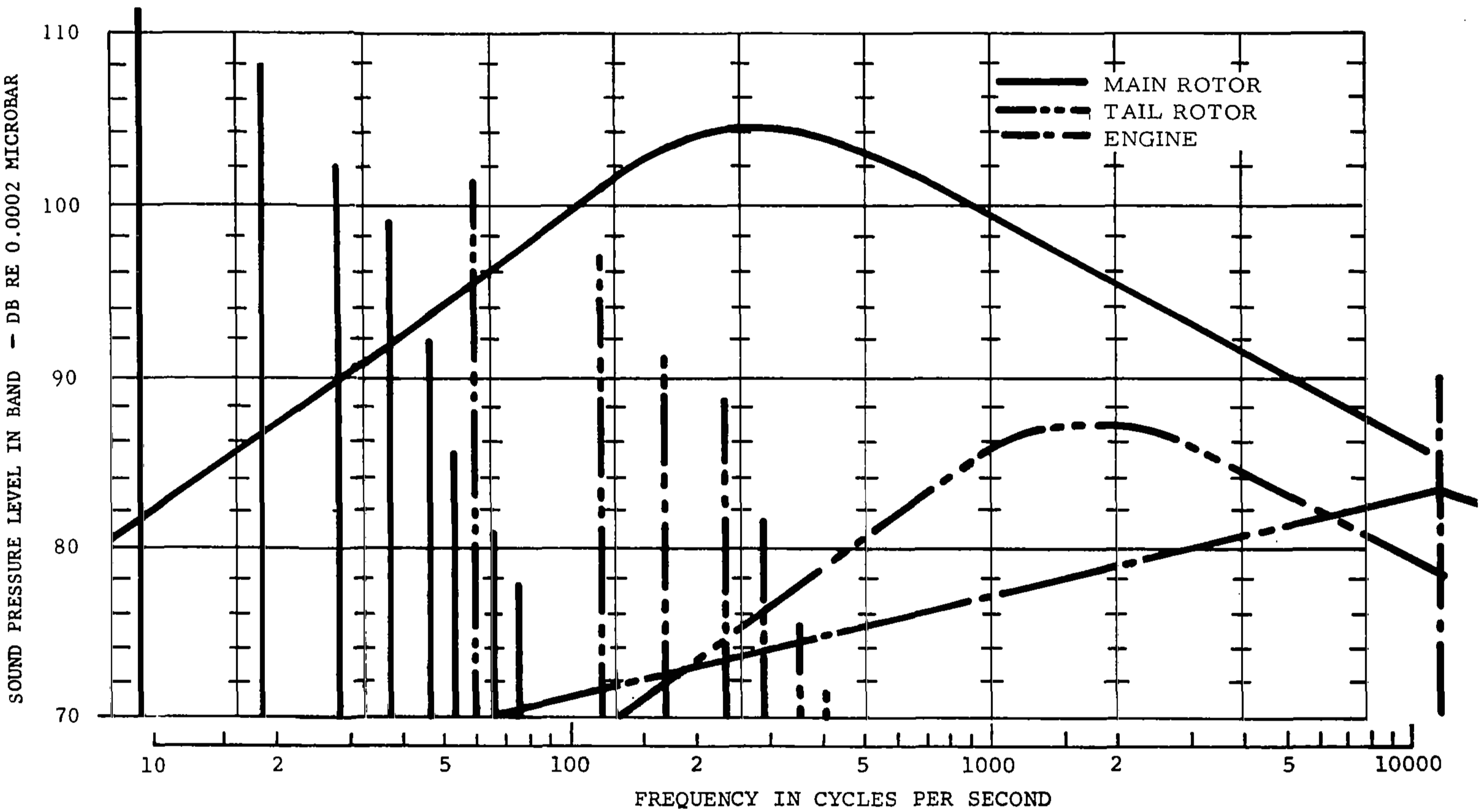


Figure 33. Rigid Rotor Terminal Spectrum.

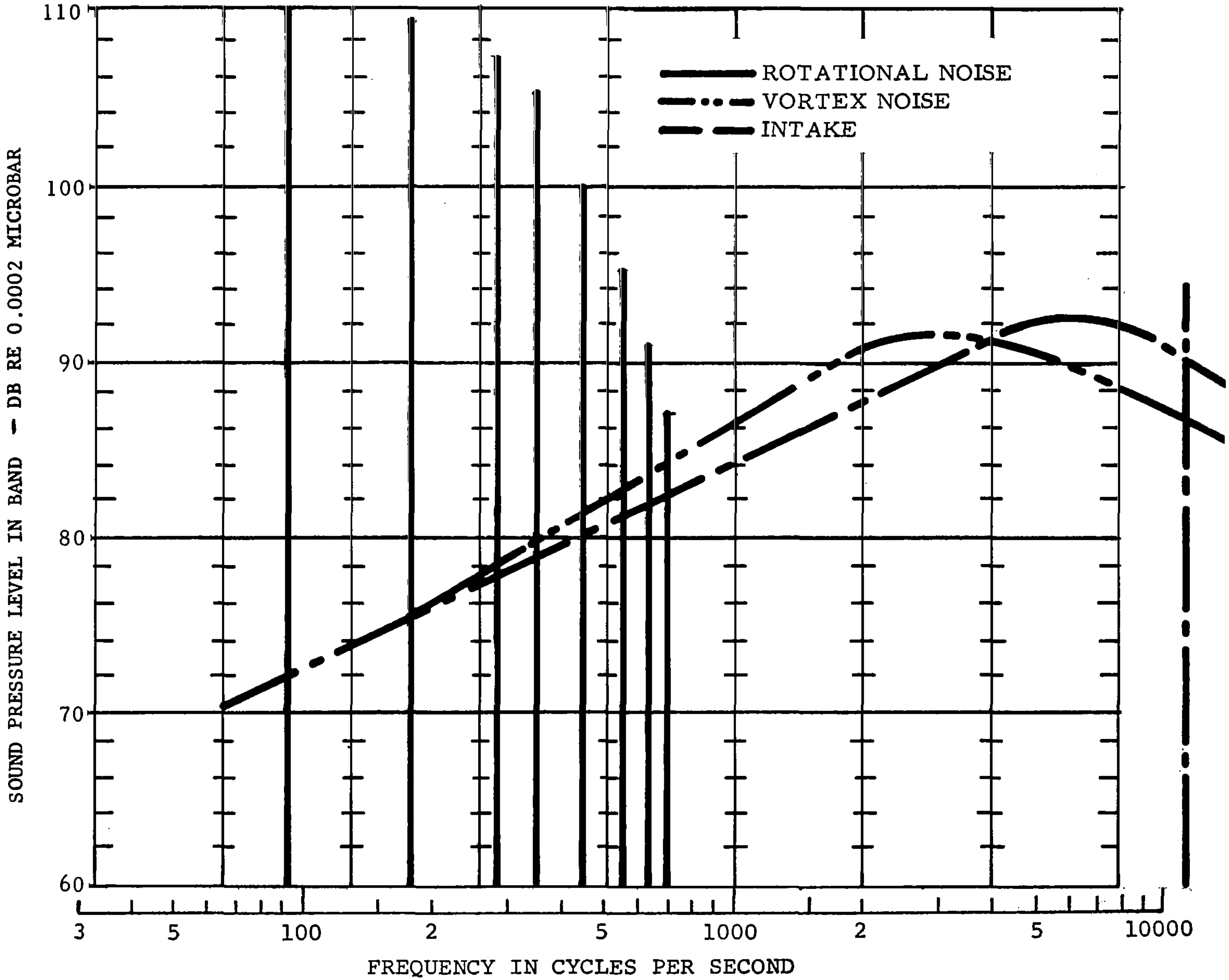


Figure 34. Rigid Rotor Cruise Spectrum.

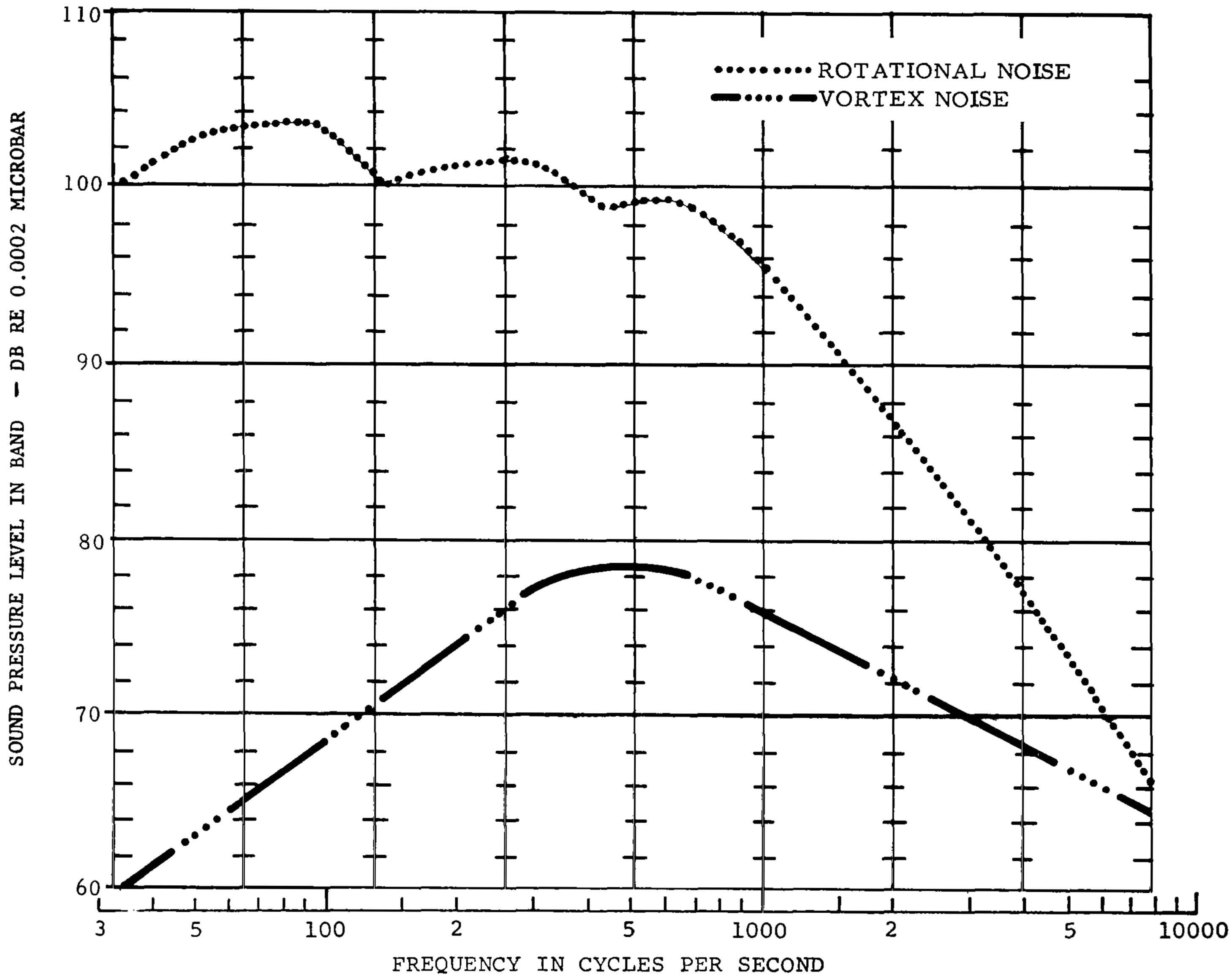


Figure 35. Tandem Rotor Terminal Spectrum.

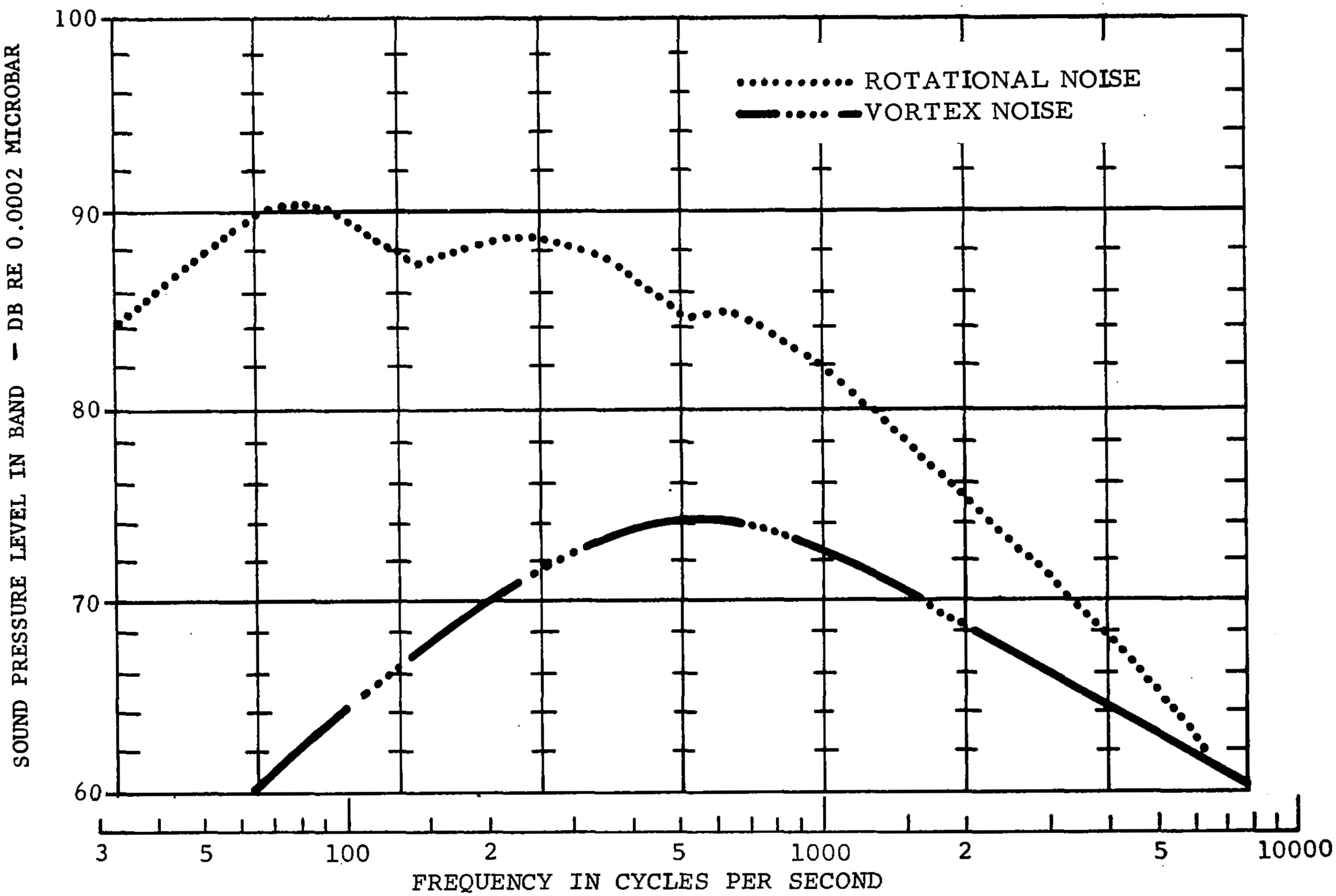


Figure 36. Tandem Rotor Cruise Spectrum.

study by including an acoustical helicopter signature with blade-bang (Figure 37). The envelope of the main rotor rotational harmonics exhibits peaks at frequencies specified by a detailed Fourier analysis of a single blade-bang occurrence.

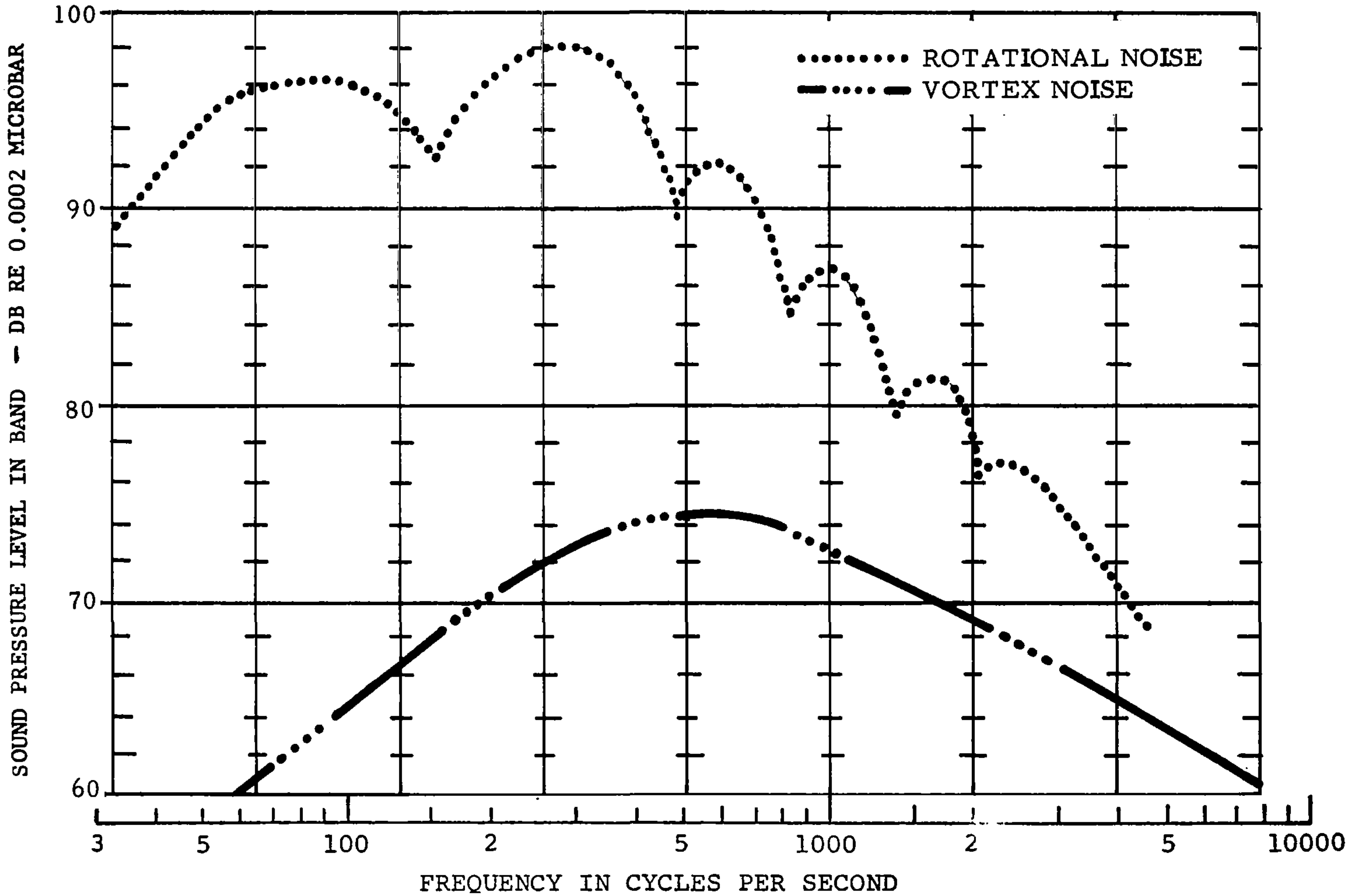


Figure 37. Tandem Rotor Cruise Spectrum With Blade-Bang.

APPENDIX B

SYNTHESIS OF INDIVIDUAL AIRCRAFT SOUNDS

Fan lift. - The terminal noise signature was synthesized by purely electronic means. Pure tone frequencies were produced by audio-sine wave signal generators. These tones represented the discrete frequencies emitted from the engine and gas generator intakes. Distributed about these tones were two shaped broad-band spectra representing some of the random noises emitted from these components. Broad-band noise from the control nozzles near the forward section of the aircraft was also separately generated and shaped to the predicted spectrum. All of these, four pure tones and three broad-band noises, were then combined in an electronic mixer and recorded at their proper amplitude ratios relative to each other on one track of a multitrack magnetic tape recorder. This combined signal was, on playback, fed to the forward facing speaker on the vehicle later used in the field simulation of the flight noise. Five minutes of this steady-state sound was recorded to allow for sufficient time for speaker volume adjustments, vehicle speed, and simulated flight path during the out-of-doors re-recording.

Similarly, seven pure tones, representing discrete harmonics of fan noise were produced. Also, shaped broad-band random noise was used to simulate the deflected cruise engine exhaust. Along with the broad-band nozzle noise, these sounds were all mixed electronically to create the sound to be directed out of the speaker facing at right angles to the direction of simulated flight.

Finally, the same gas generator pure tone and broad-band noise created for the forward facing speaker were recorded on a third track of the tape recorder for playback through the speaker which faced to the rear of the vehicle.

Since the fan lift aircraft in cruise is a more or less conventional by-pass fan jet, it was decided to reshape the fly-over sound of an actual turbofan aircraft to the spectrum shape predicted for this fan lift aircraft.

Jet lift VTOL. - The jet lift VTOL terminal noise, like that of the fan lift terminal noise, was produced entirely by electronic means. Pure tones and shaped random noise representing the cruise engine intake noise were mixed and recorded on track one for the forward facing speaker. The noise of the lifting jets, consisting of tones and shaped broad-band noise along with two shaped random noise sources representing primary and by-pass exhaust noise and the shaped random noise representing the deflected cruise engine exhaust noise were then combined and recorded for playback out of the side speaker. The third speaker was used only to round out the noise distribution with some simulated cruise engine deflected exhaust noise.

The remainder of the simulation procedure, including out-of-door amplitude-time history and directivity, and laboratory refinement of spectral shape and final adjustments was identical to that used for the fan lift terminal noise.

For reasons discussed in the noise analysis section of Appendix A, a separate cruise noise simulation of this aircraft was omitted and another helicopter noise signature was substituted in the study.

Tilt wing VTOL. - For more realism, it was decided to use frequency and amplitude shifted propeller noise from an actual tilt wing in hover, the VZ-2, rather than simulate rotor or propeller terminal noise. However, since the VZ-2 has a tail rotor in addition to its main rotors, an analysis had to be performed of the azimuthal noise distribution. This was done by tuning a narrow-band filter to the fundamentals of the main and tail rotor rotational noise frequencies. A record of the noise ratio of main rotor to tail rotor amplitude revealed that at the 12 o'clock azimuth location (directly in front of the aircraft) the tail rotor noise was inaudible and more than 15 decibels below the main rotor noise. Therefore, the main rotor noise recorded at this azimuth location was used, although it was shifted from the fundamental of 70 Hz for the VZ-2 to the predicted frequency of 50 Hz for the tilt wing noise to be simulated. This frequency shift was done with the variable speed tape recorder. The amplitude shaping was accomplished with a one-third octave-band equalizer.

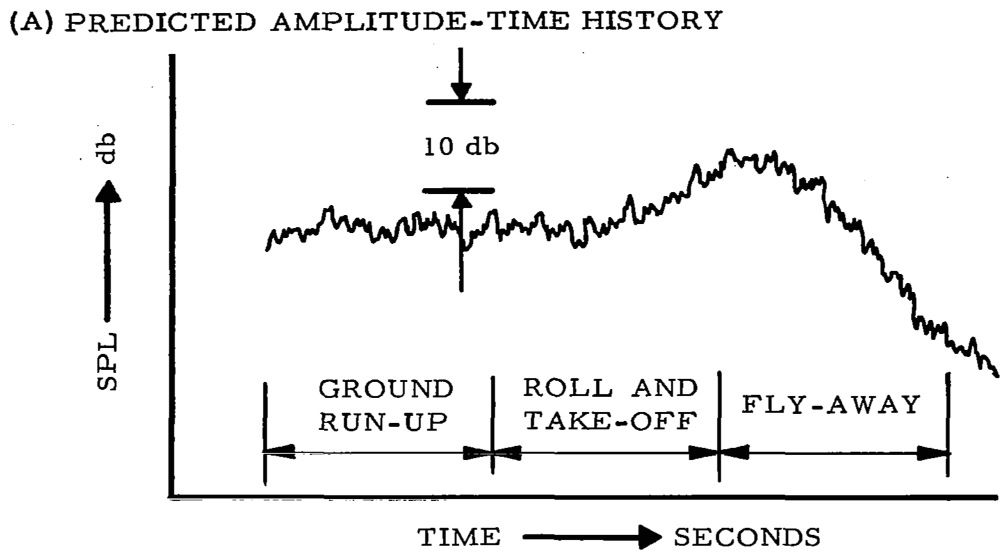
This procedure then resulted in the proper frequency content and amplitude distribtuion of the tilt wing rotor rotational noise. Propeller blade vortex noise, being of insufficient magnitude to scale from the VZ-2 tilt wing, was generated electronically by a random noise generator and amplitude shaped. Thus, the tilt wing blade noise spectrum was composed, mixed and radiated from the side speaker of the vehicle used in the simulation process.

A pure tone with shaped broad-band random noise centered about this frequency represented engine intake noise emanating from the simulation vehicle front speaker. And, to round out the sound distribution behind the vehicle, some of the broad-band noise was fed to the rear speaker.

The remainder of the simulation procedure was the same as for the other field-synthesized amplitude-time histories: directivity from the vehicle speakers, amplitude-time from driving past the microphone, and final spectrum adjustments in the laboratory. The procedure for creating the cruise noise was similar to that for obtaining the tilt wing terminal noise with several modifications. Blade rotational noise of the VZ-2 was shifted to a fundamental of 30 Hz instead of 50 Hz used for the terminal operation. The spectrum shape was somewhat different from the terminal noise and was again adjusted with the octave band equalizer. The amplitude-time history, obtained by vehicle speed variations, was different from the terminal noise time history. Finally, after the field simulation was completed, Doppler shift was introduced artificially by the variable speed tape recorder by playback onto another recorder.

Turbofan STOL. - The turbofan STOL takeoff noise was primarily derived from a real aircraft fly-over noise. The actual turbofan noise, however, was augmented by shaped random noise preceding the peak amplitude during the fly-by. Figure 38 illustrates the technique of simulating this STOL aircraft noise during takeoff. Part (a) of the figure shows the predicted time history of the STOL aircraft considering the ground run-up noise generated 2000 feet from the takeoff point, the takeoff, and the fly-away noise. Part (b) of Figure 38 indicates that shaped random noise was generated electronically, preceding the spectrum shaped actual turbofan noise fly-over. The mixed sum of these two component noises yielded the predicted amplitude-time history of the STOL takeoff noise.

The spectrum and amplitude-time history of the turbofan cruise noise was relatively simple to simulate. The sound from an actual by-pass turbofan fly-over was shaped to the required spectrum with the octave band equalizer. The resulting acoustical signature represented the predicted noise level for the turbofan in cruise at an altitude of 2000 feet.



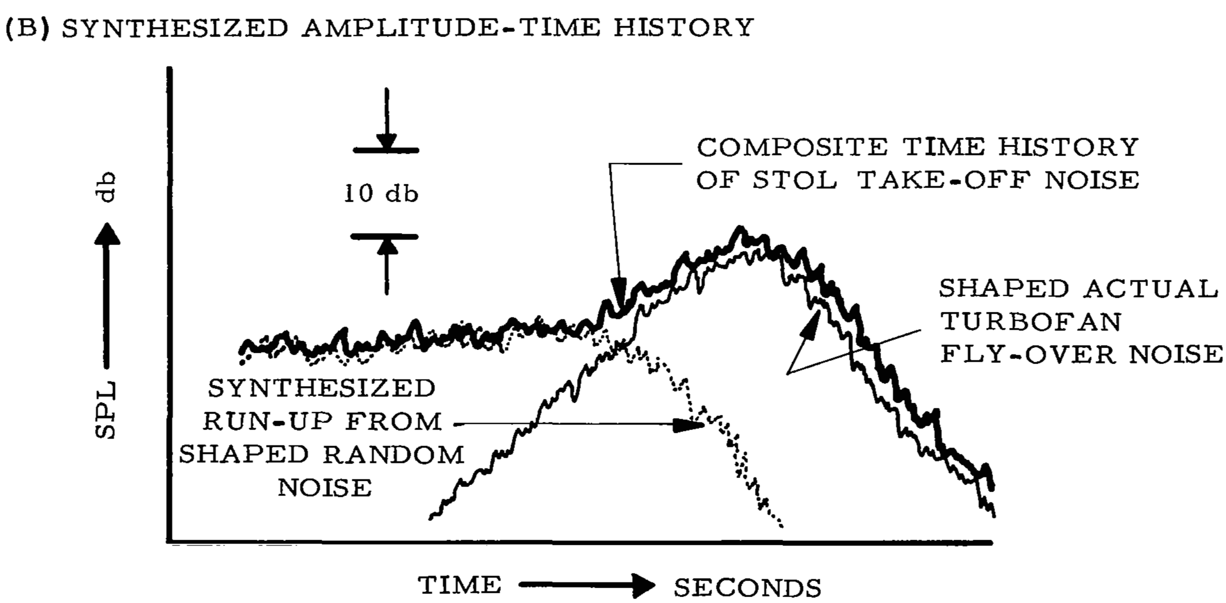


Figure 38. Simulation of Turbofan STOL Terminal Noise.

APPENDIX B

Rigid rotor VTOL. - The synthesis of rigid rotor helicopter terminal noise was accomplished with the aid of actual single rotor helicopter noise. A frequency shift of the real helicopter rotor rotational noises, the fundamental and harmonics of the blade passage frequency, was made on the variable speed tape recorder. The new frequency-shifted spectrum was then refined with the use of the octave band equalizer to the shape predicted by analysis.

Since the rigid rotor VTOL aircraft was converted to a conventional propeller aircraft, the synthesis of the cruise noise was accomplished in the same manner as that of the noise of the tilt wing. Component noises from which this aircraft acoustical signature was assembled included some reshaped and frequency shifted actual propeller rotational noise, an electronically synthesized broad-band vortex noise represented by a random noise generator shaped output, and pure tone and shaped broad-band noise to simulate engine noise. Then, in the field, the amplitude-time history and directivity factors were composed with the mobile sound generator. And, finally, laboratory refinements in spectrum shape, time history, and the inclusion of the artificial Doppler effect were combined to yield the desired cruise fly-over noise.

Tandem rotor VTOL. - The tandem rotor helicopter terminal noise signature, like that of the rigid rotor during terminal operation, was constructed with the aid of taped sounds of an existing helicopter. Because the helicopter design of this study had four blades on each of the two main rotors instead of the three blades on the sample available, the blade passage noise frequency and its harmonics were shifted slightly upwards along the frequency scale with the aid of the variable speed tape recorder. Adjustments in spectrum shape to coincide with that predicted by analysis were made with the octave band equalizer and resulted in the noise predicted for the future tandem rotor of this study.

Both banging and nonbanging tandem rotor helicopter noises representing cruise flight noise conditions were simulated. Actual tandem rotor cruise fly-over noise, frequency shifted and amplitude shaped as for the terminal noise conditions, was used.

APPENDIX C

SPECTRUM ADJUSTMENTS BY APPARENT DISTANCES

As discussed previously, it had been decided to evaluate a range of stimulii encompassing four levels for each of the twelve aircraft sounds, two above and two below the anticipated midpoints of equivalent annoyance. Furthermore, these four levels were not to represent simple settings of a volume control, but actual spectra, shaped by apparent effects of distance and atmospheric sound absorption in order to simulate four different distances of the aircraft from the intended listener. The method of determining what these spectra should be will be illustrated by using the terminal noise spectra of the fan lift VTOL aircraft as an example (Figure 39). The steps involved are discussed below.

<u>Step 1</u>. - Starting with the acoustical spectrum predicted for a 500 foot distance from an outdoor observer (spectrum a), adjustments were made for wall sound transmission loss for the intended indoor listener (spectrum b).

<u>Step 2</u>. - This sound, when presented to the listeners in the preliminary (volume adjust) test, was then adjusted by the listeners to various levels from which the median (spectrum c) was chosen for further calculations.

<u>Step 3</u>. - The peak PNdb level of spectrum c as defined in reference 9 was then determined. However, because the adjustments during the preliminary tests were made on a volume basis, all octave band levels were reduced by an equivalent amount. Since any change in level necessary for actual subjective testing was to consist of changes in apparent distance, the reductions in the various octave bands should have been nonlinear with frequency. Therefore, a new spectrum d was found with a perceived noise level (PNL) equal to that of spectrum c. This now represented the distance this simulated aircraft would have to be from an indoor listener to produce the PNL of spectrum d. This distance was determined with the aid of reference 18.

<u>Step 4</u>. - Spectrum d then was the anticipated midpoint about which the four levels of each of the twelve stimulii were to be varied. Again, four spectra representing four

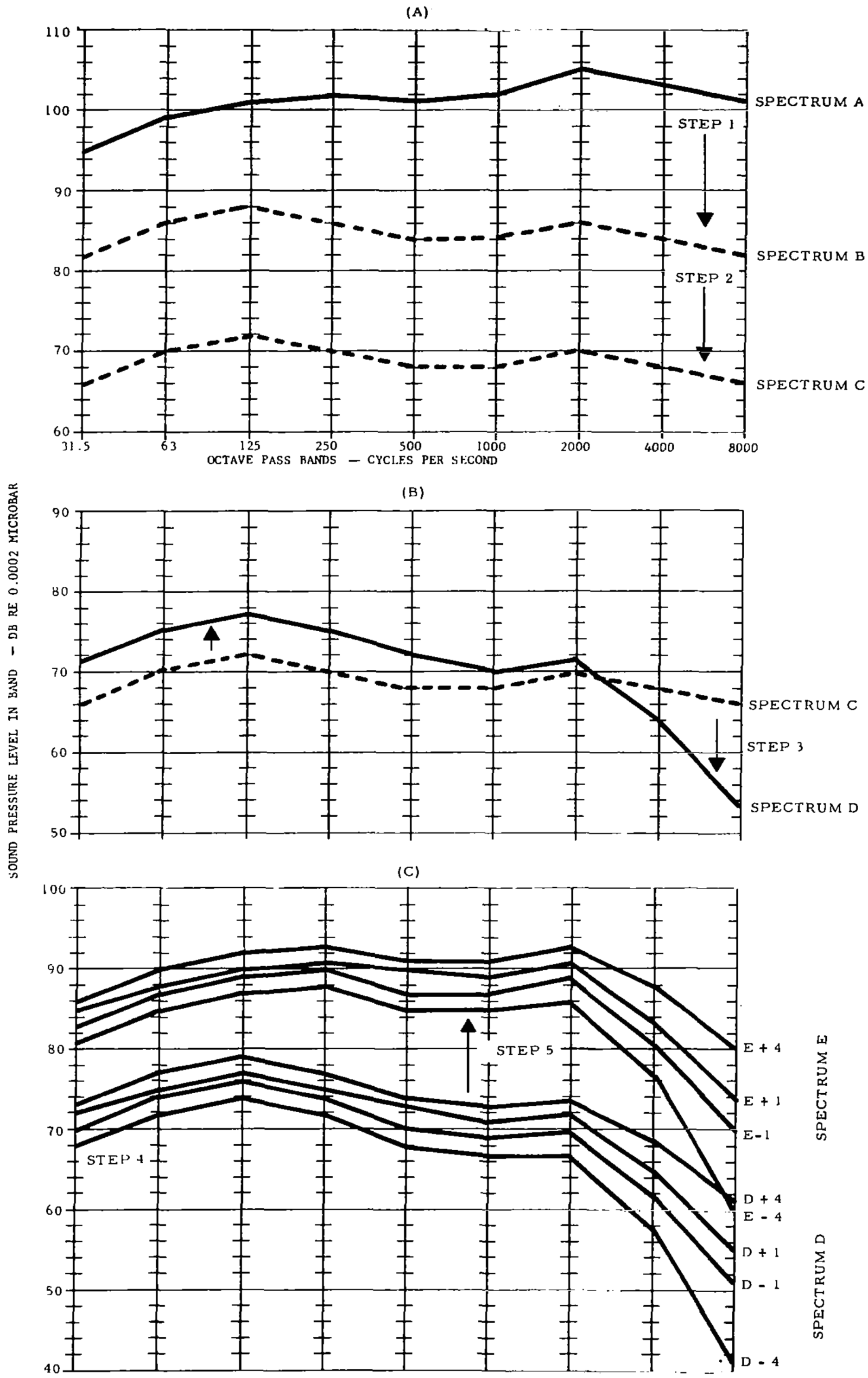


Figure 39. Procedure for Spectrum Adjustments.

different distances were found corresponding to +4, +1, -1, and -4 PNdb about the PNL of spectrum d.

Step 5. - Since the sounds, although intended to be heard as indoor sounds, were to be simulated on magnetic tape as outdoor sounds, the db differences due to wall transmission loss for the various octaves were added.

The transition from spectrum a, Step 1 (on magnetic tape when the volume adjust test was administered) to the four spectra in Step 5 was accomplished in the Acoustical Laboratory. The extent of the changes was observed on an octave band analyzer with graphic level recorder as a readout device. Spectra were also monitored aurally during this process.

Final Magnetic Tape Preparation

In the administration of the paired comparison test, it was originally planned to account analytically for the sample order error. This error occurs when the second one of a pair of stimulii is generally rated as being dominant whereas actual instrument analysis measures both the same. In reference 1, the error for auditory stimulii was reported to be two decibels. However, results of a more recent investigation (reference 17) indicate that the correction is not necessarily a constant. The spectra, their relative amplitudes, and the absolute magnitudes of the sounds being compared play an interacting role in determining this correction. Consequently, both test sequences were presented to the subjects, that is, the reference sound in the pair would be heard first (R-S sequence), and at another time, it would be heard last by the same test subjects (S-R sequence). Thus, two comparisons of each of the 48 stimulii were planned for presentation to the test subjects to determine and account for order error.

The final tape sequence presented to the test subjects for the paired comparison test was randomized. This was done with the aid of a random numbers table from reference 19 and resulted in a mathematical random sequence involving aircraft types, mode of operation, sound level, and order of presentation.

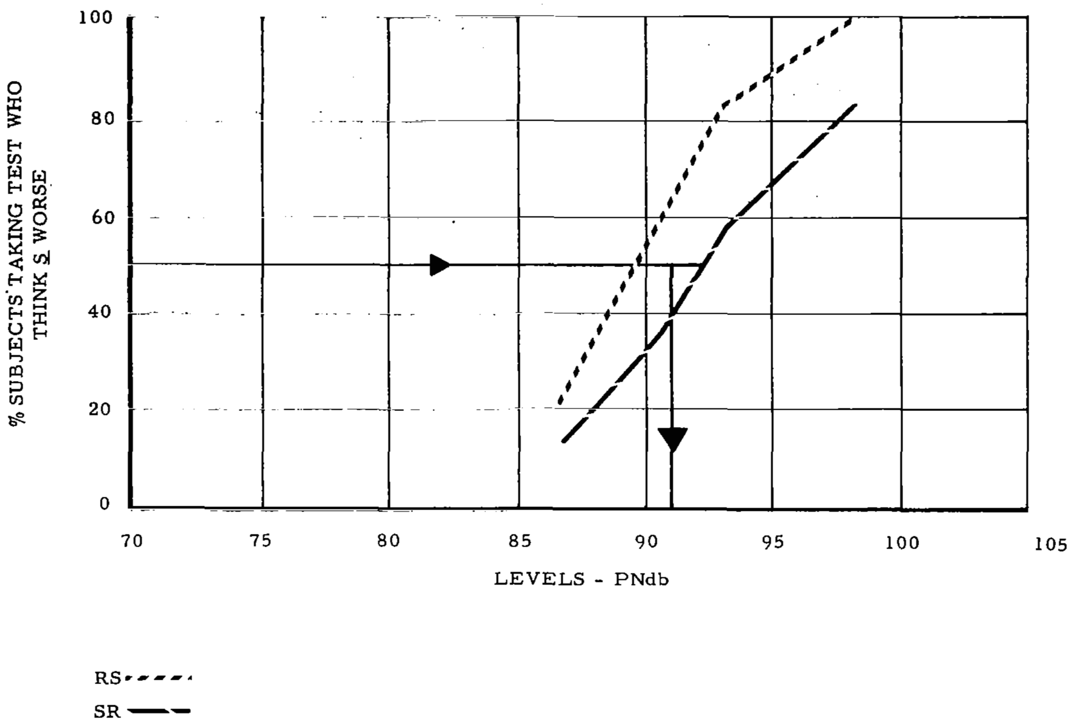
APPENDIX D

DERIVATION OF COMPARATIVE PEAK PNdb BASED ON MEASURED INDOOR SPECTRA

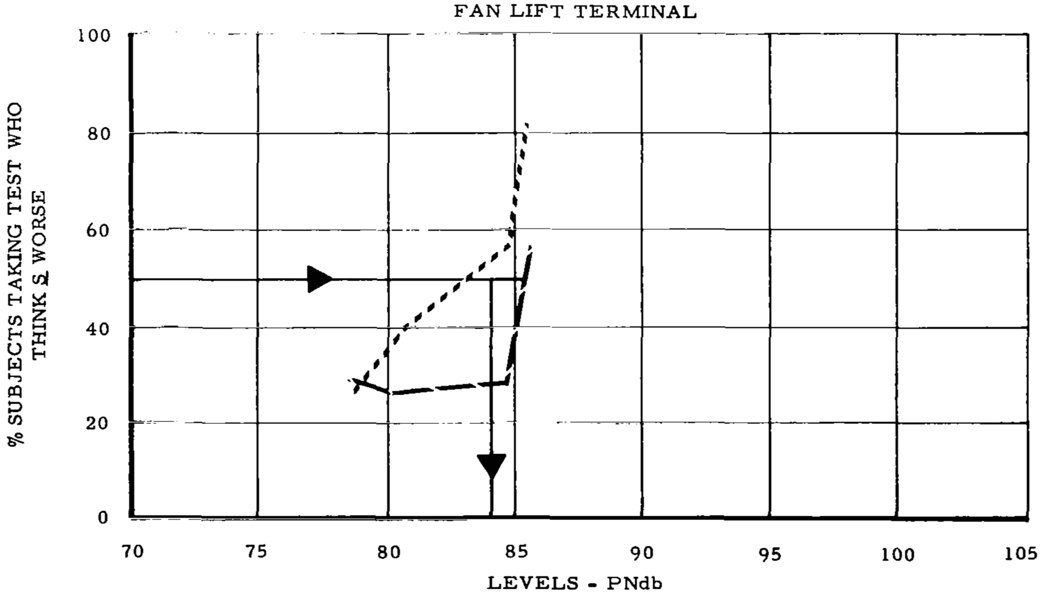
This Appendix contains the correlation of subjective and objective data which yield the comparative peak perceived noise level based on measured indoor noise spectra. The dotted line represents the response to the stimulus when it was heard in the second of the two positions in each pair of sounds. The dashed line is the response to the other stimulus position in the pair, i.e., the stimulus was presented before the reference.

APPENDIX D

FAN OR JET LIFT CRUISE
MEASURED PNdb LEVELS



FAN LIFT TERMINAL

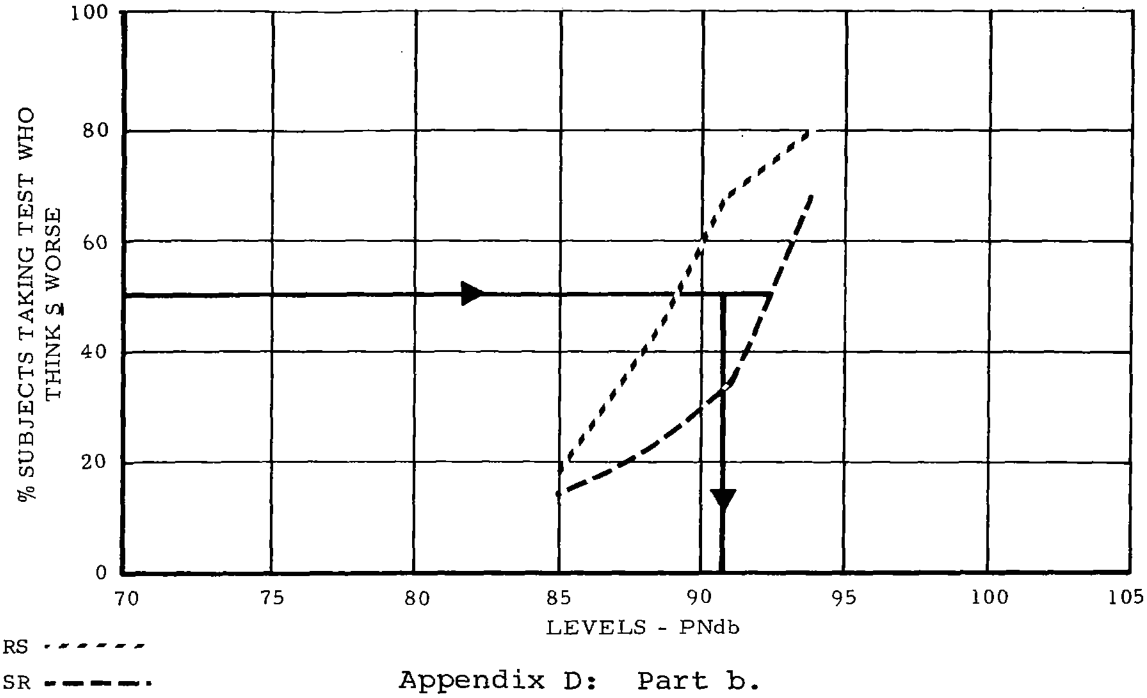


Appendix D: Part a.

APPENDIX D

BANGING TANDEM ROTOR CRUISE

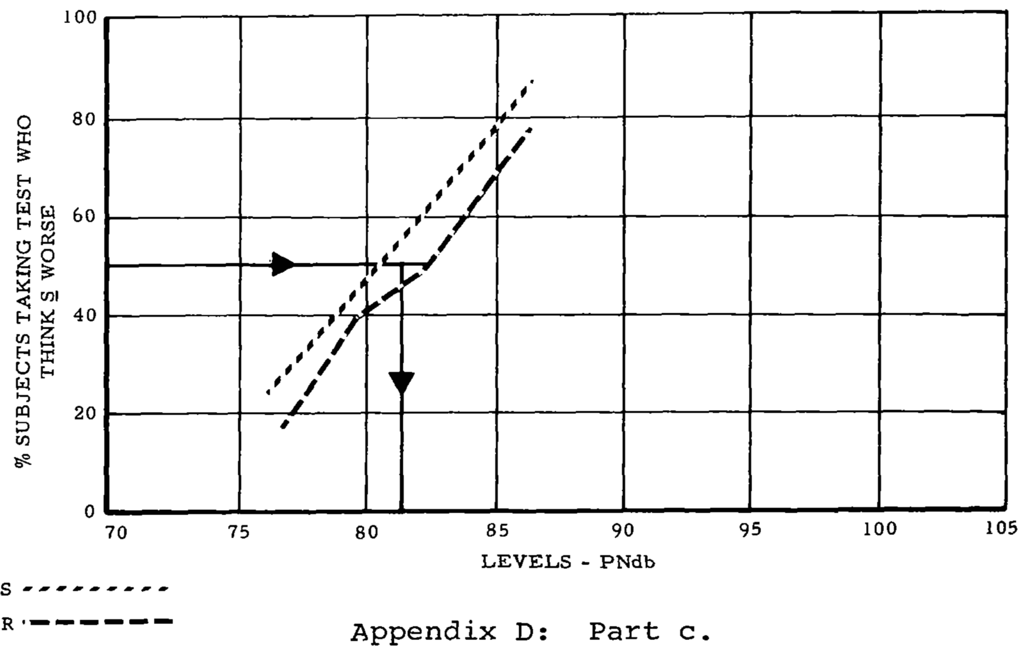
(MEASURED PNdb LEVELS)



Appendix D: Part b.

SUBJECTIVE TEST RESULTS
(MEASURED PNdb LEVELS)

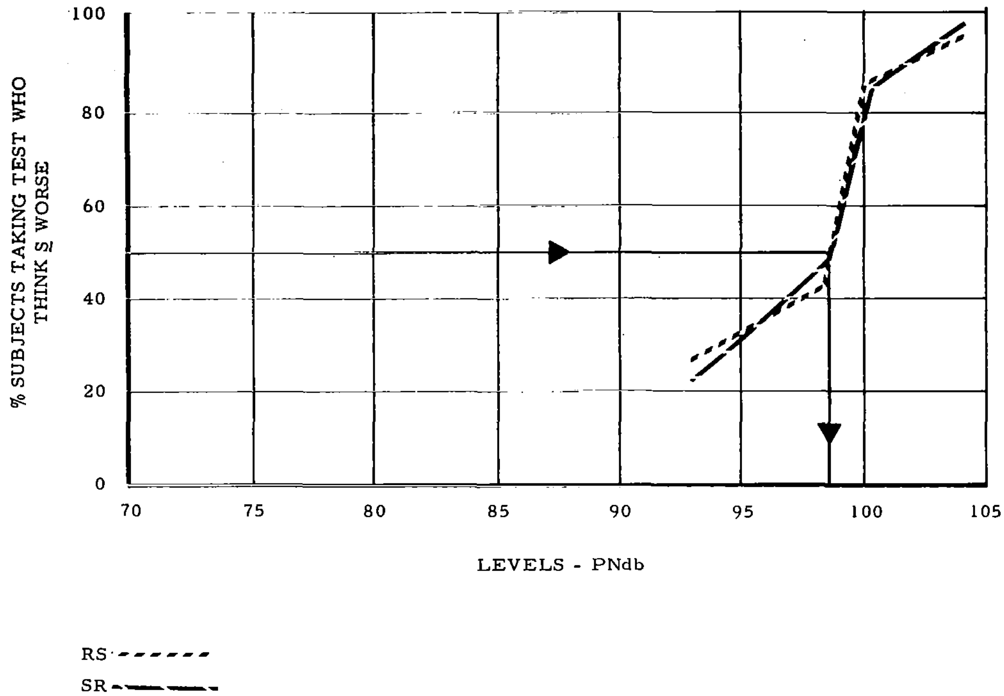
JET LIFT TERMINAL



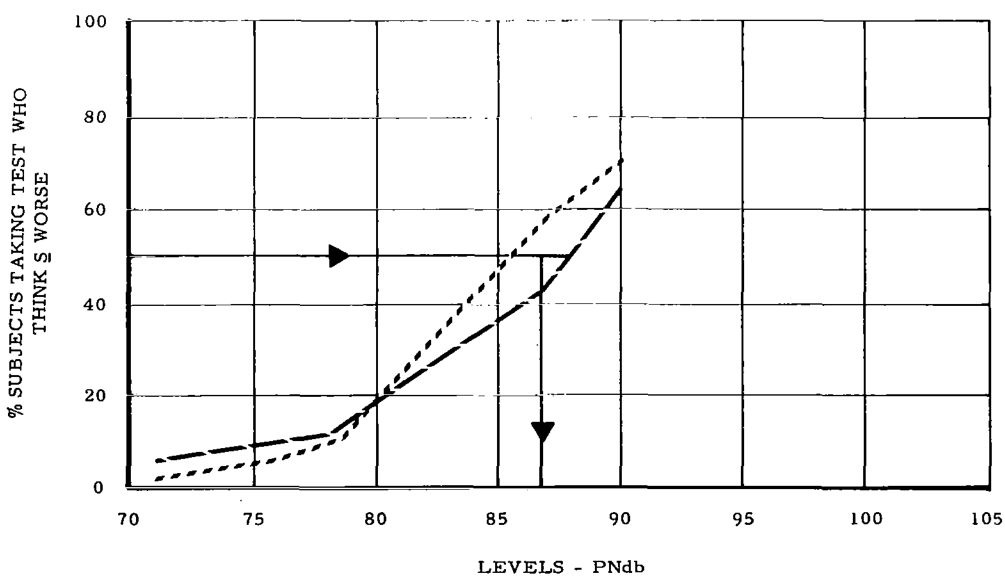
Appendix D: Part c.

APPENDIX D

TILT-WING CRUISE
(MEASURED PNdb LEVELS)



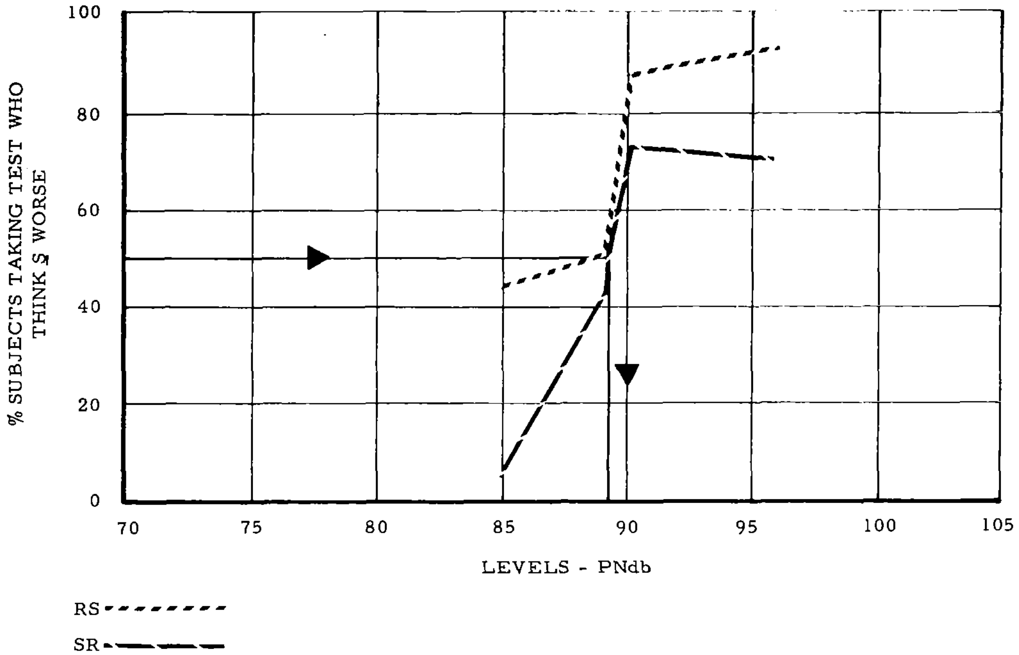
TILT WING TERMINAL



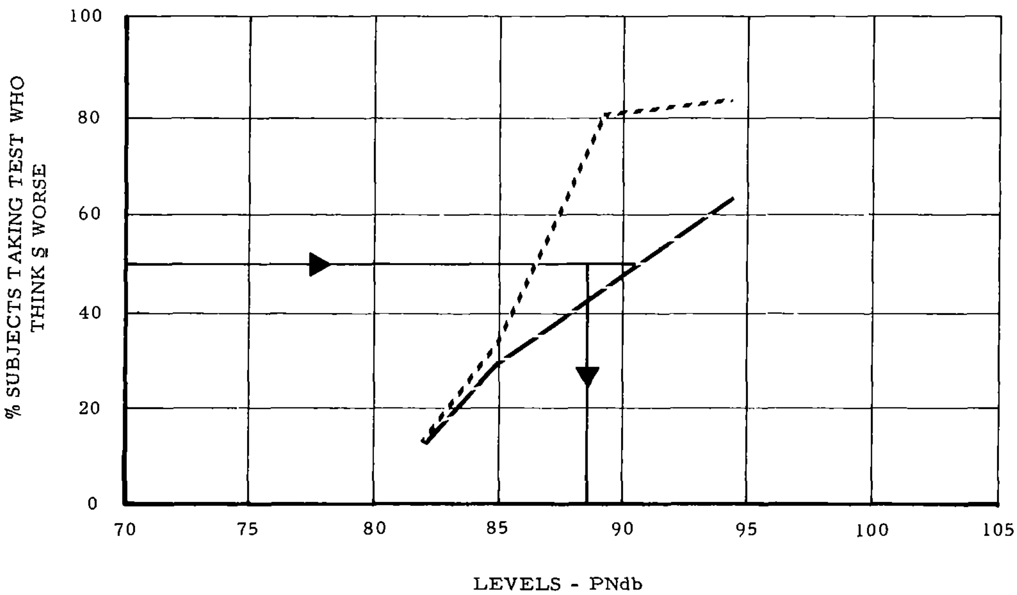
Appendix D: Part d.

APPENDIX D

TURBO-FAN STOL CRUISE
(MEASURED PNdb LEVELS)



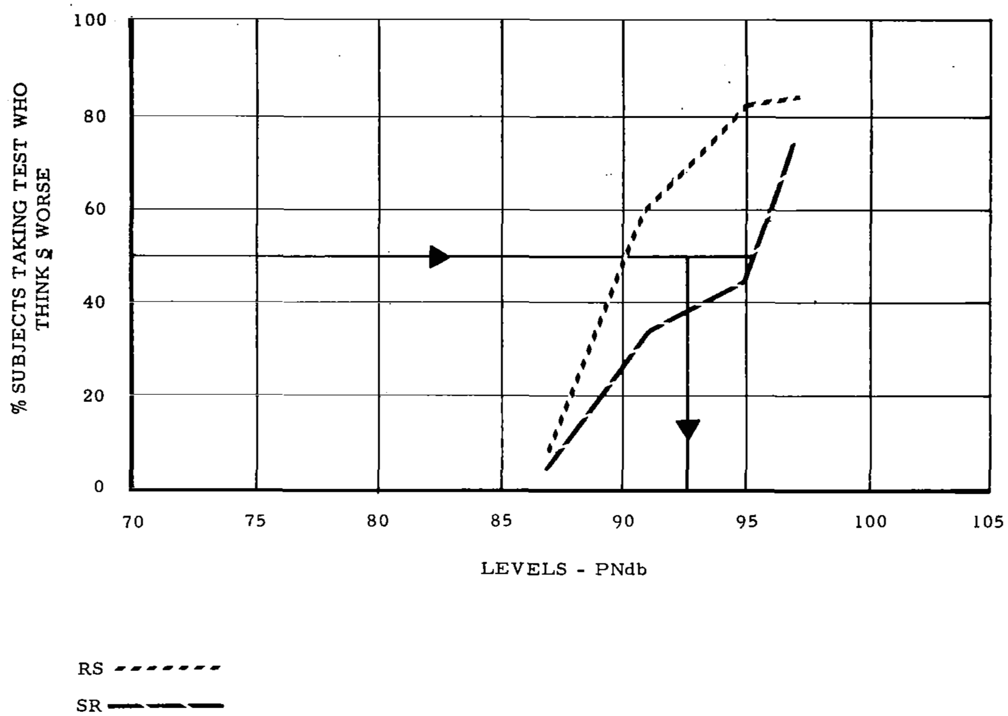
TURBO-FAN STOL TERMINAL



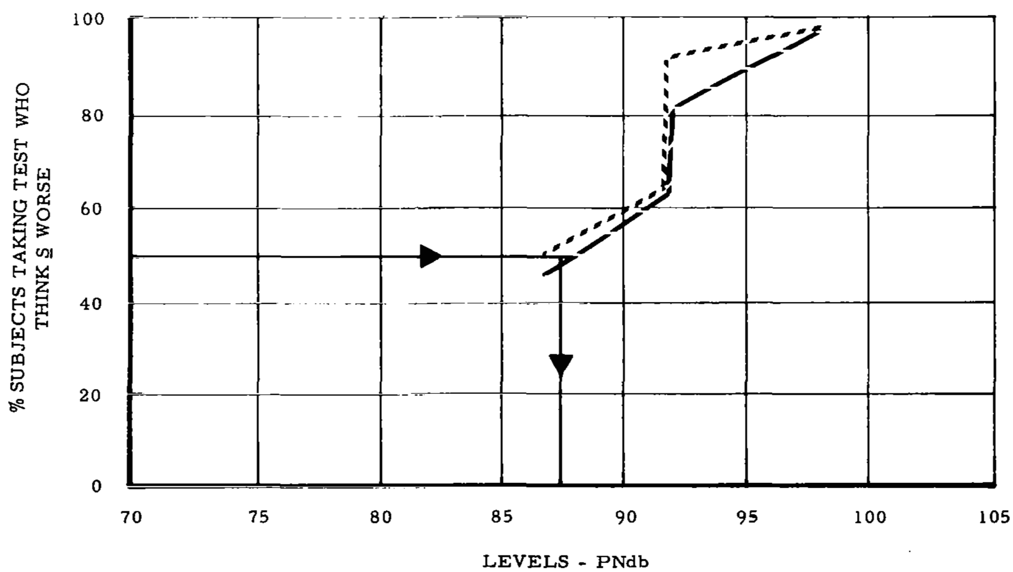
Appendix D: Part e.

APPENDIX D

RIGID ROTOR CRUISE
(MEASURES PNdb LEVELS)

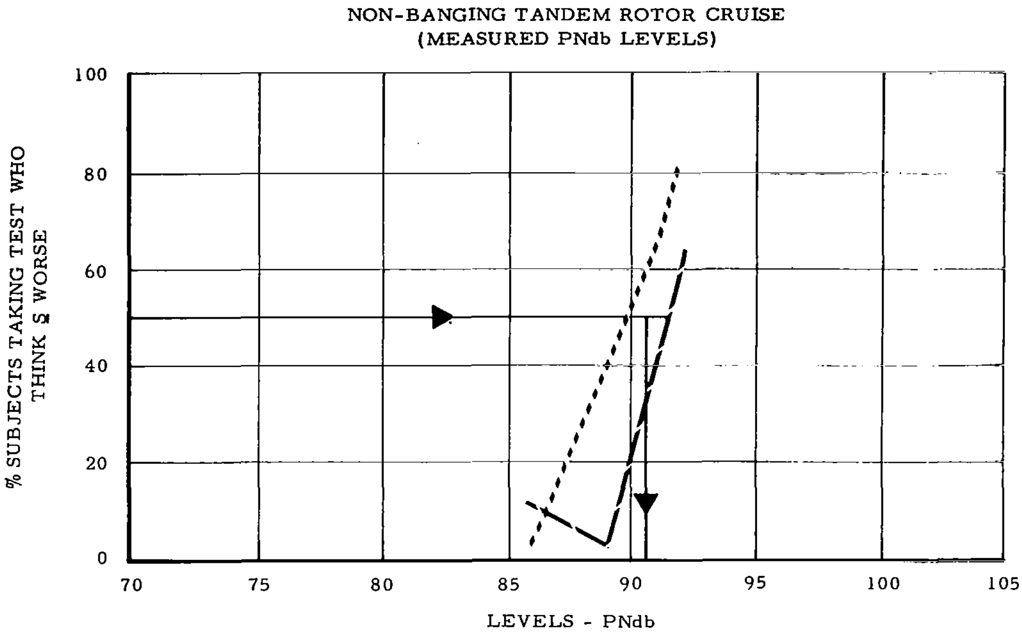


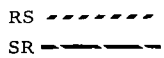
RIGID ROTOR TERMINAL

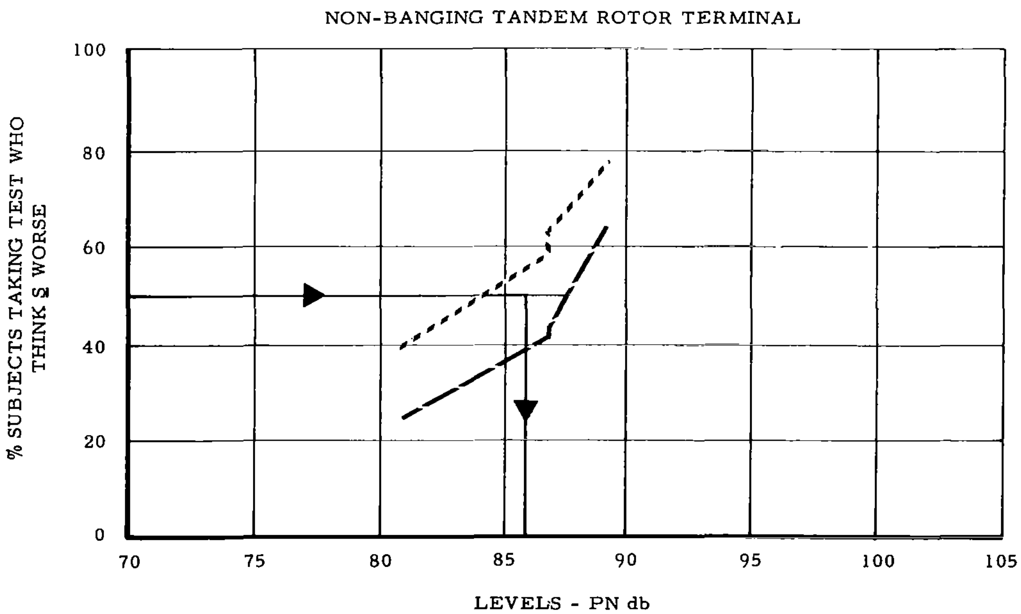


Appendix D: Part f.

APPENDIX D







Appendix D: Part g.

APPENDIX E

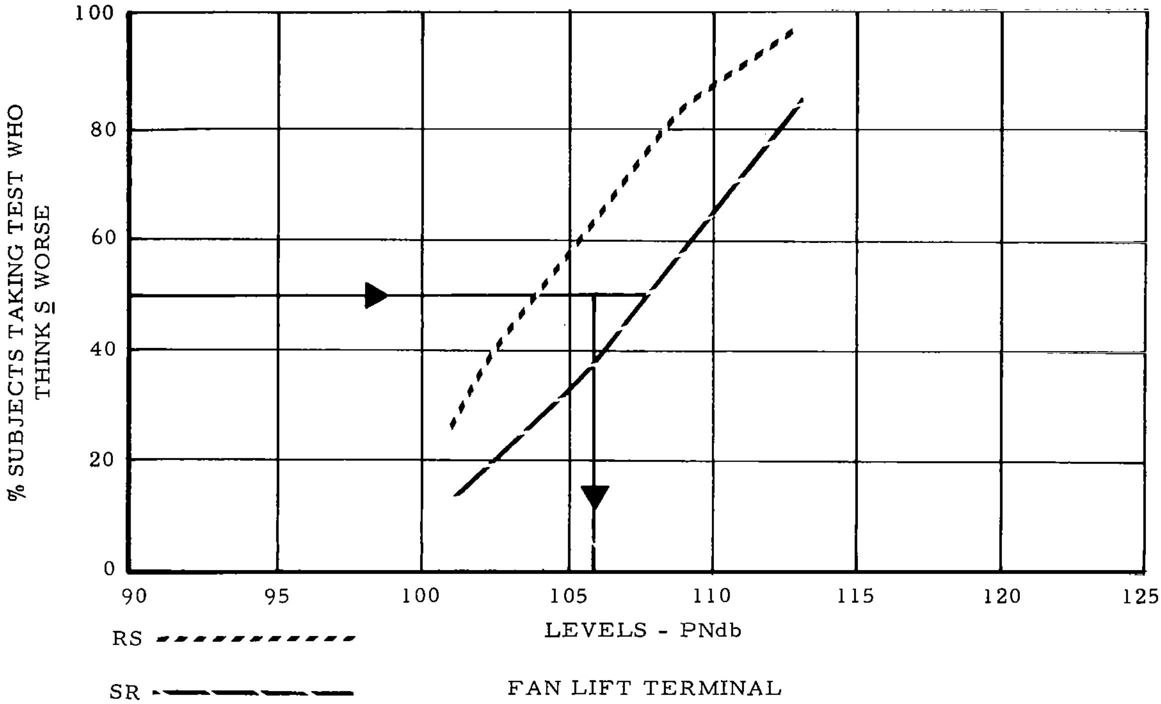
APPLICATION OF COMPARATIVE PEAK PNdb TO OUTDOOR AIRCRAFT SOUNDS

This Appendix contains the correlation of measured subjective responses and predicted acoustic data which result in the derivation of the comparative peak perceived noise level as would be determined from data measured out of doors.

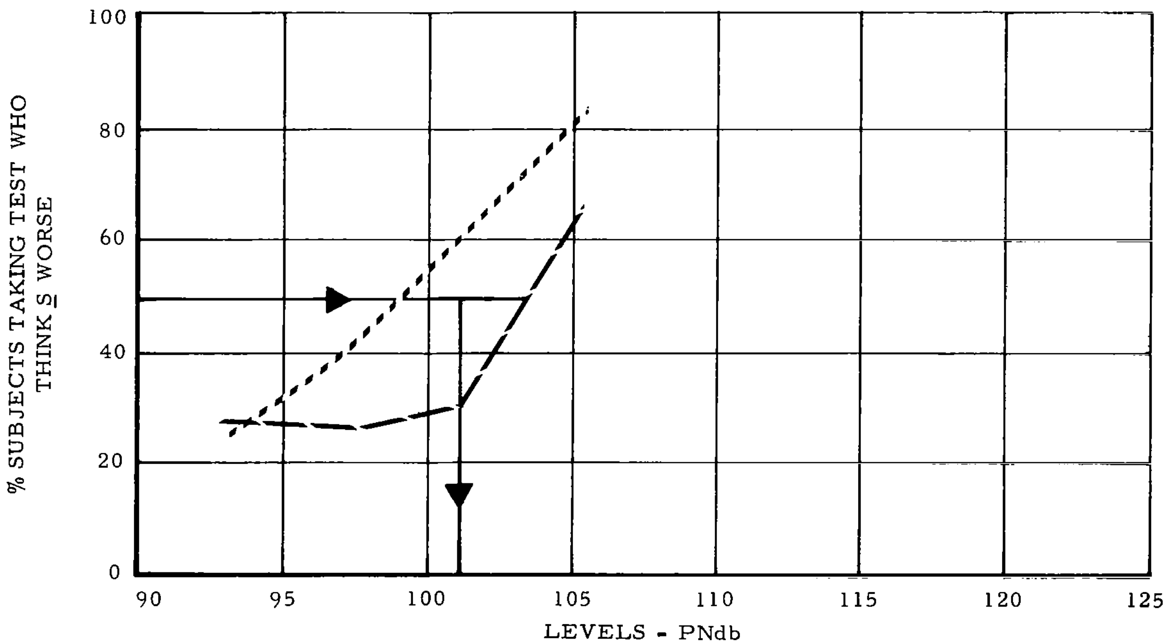
APPENDIX E

SUBJECTIVE TEST RESULTS
(OUTDOOR PNdb LEVELS)

FAN OR JET LIFT CRUISE



FAN LIFT TERMINAL

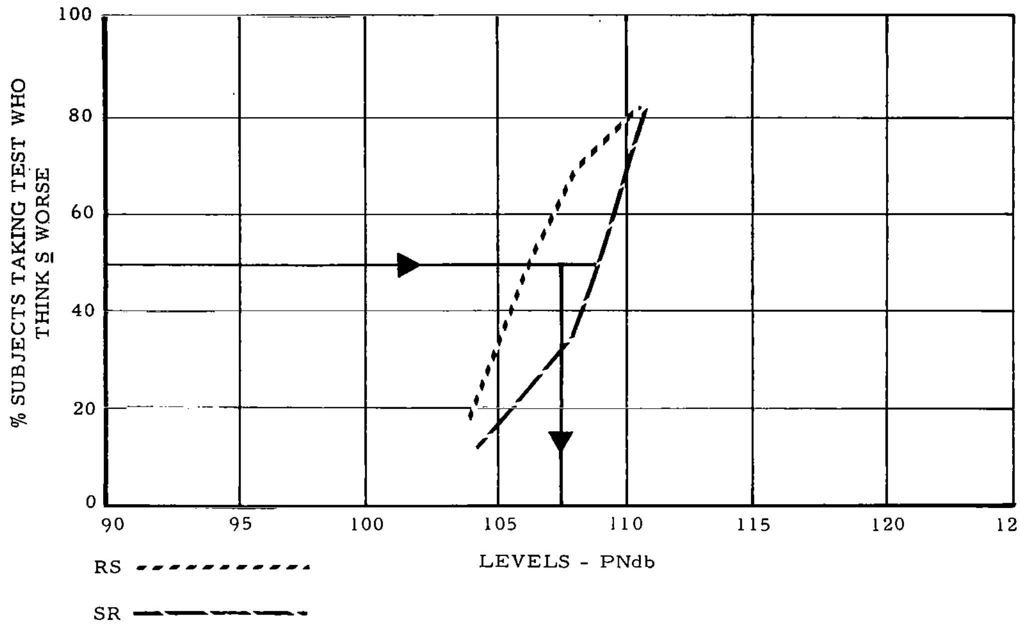


Appendix E: Part a.

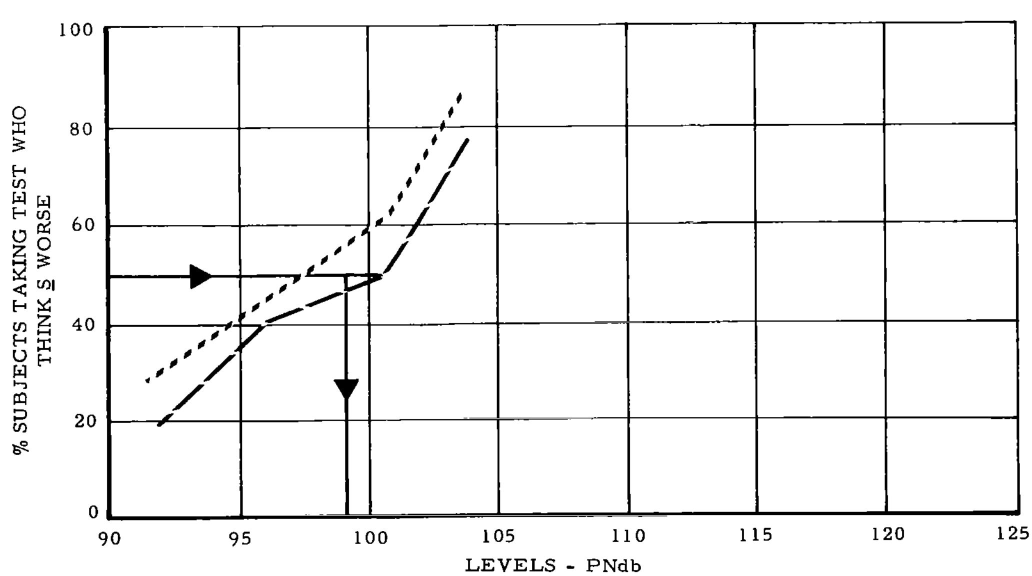
APPENDIX E

SUBJECTIVE TEST RESULTS
(OUTDOOR PNdb LEVELS)

"BANGING" TANDEM ROTOR CRUISE



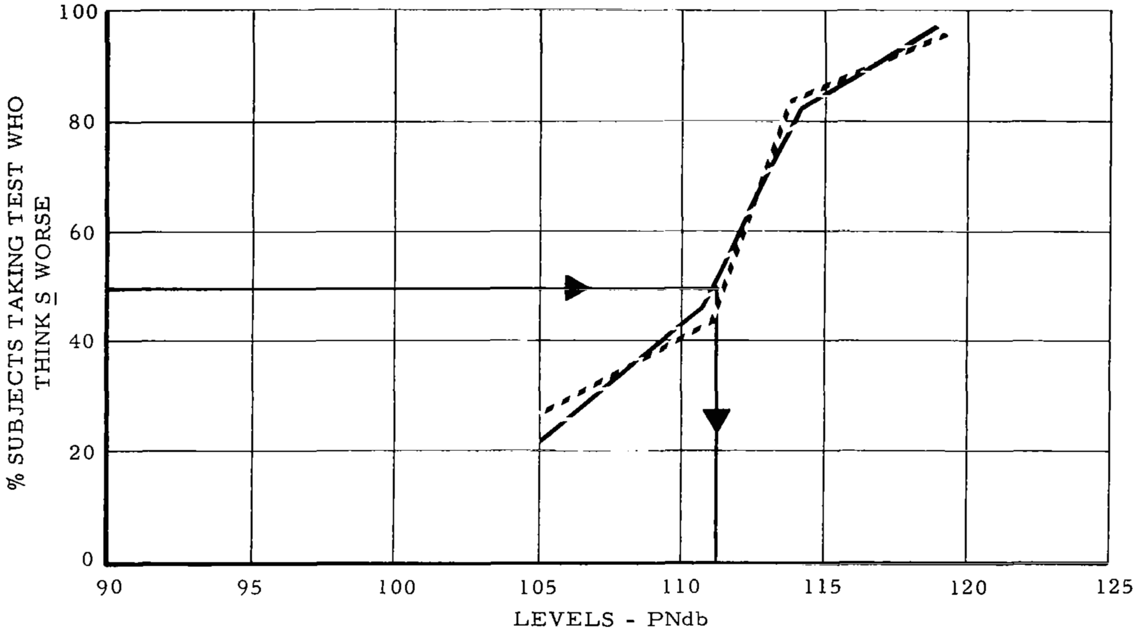
JET LIFT TERMINAL



Appendix E: Part b.

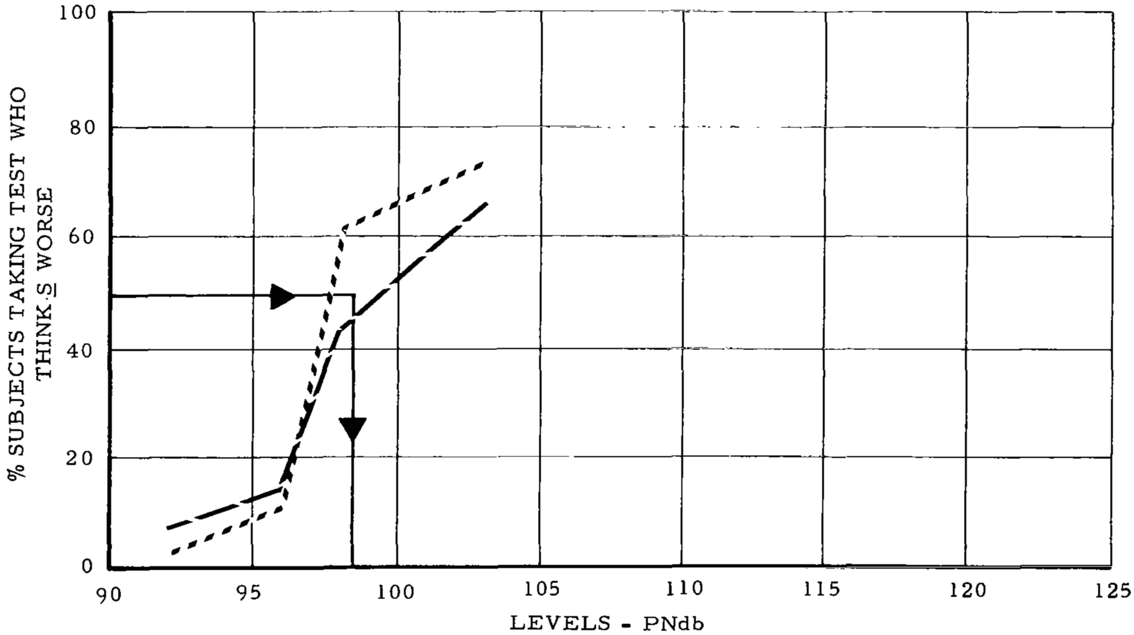
APPENDIX E

SUBJECTIVE TEST RESULTS
(OUTDOOR PNdb LEVELS)
TILT-WING CRUISE



RS
SR

TILT-WING TERMINAL

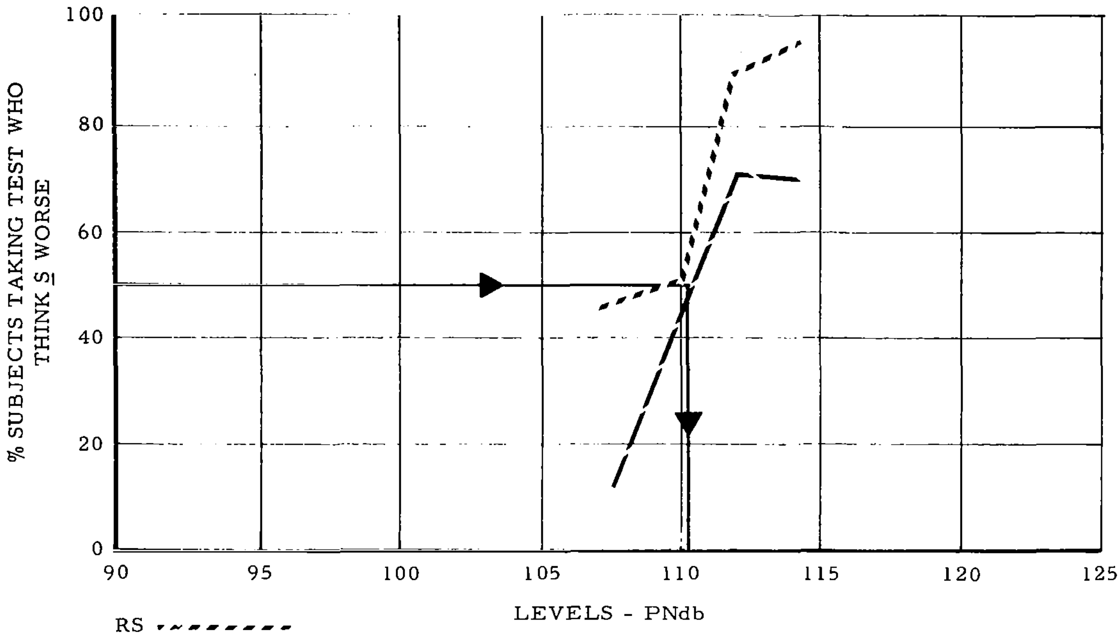


Appendix E: Part c.

APPENDIX E

SUBJECTIVE TEST RESULTS
(OUTDOOR PNdb LEVELS)

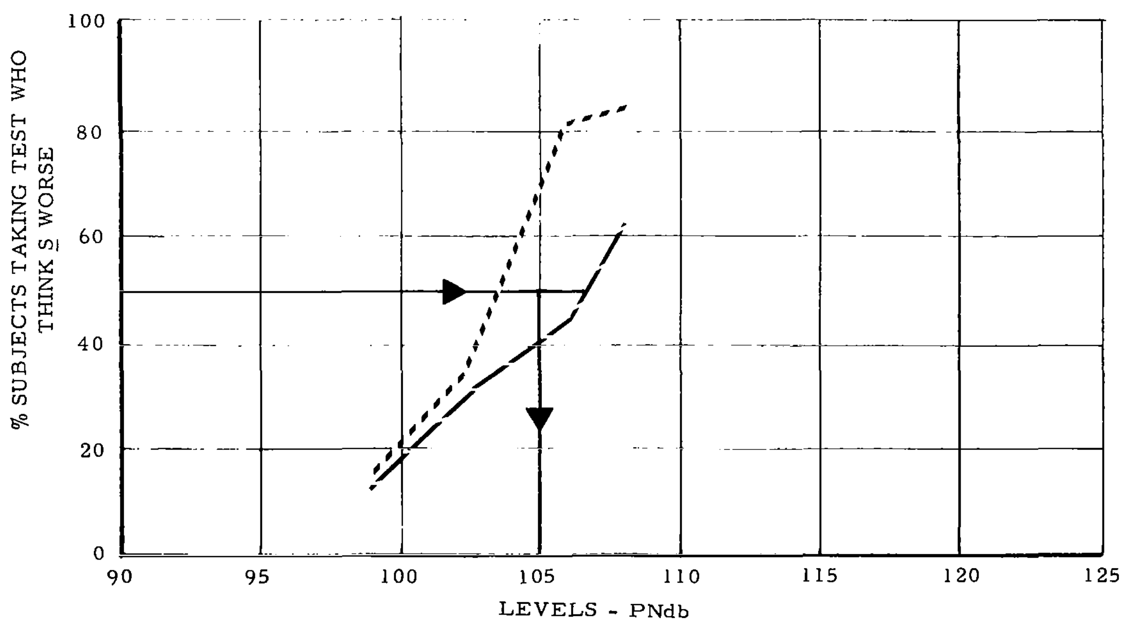
TURBO FAN STOL CRUISE



RS

SR

TURBO FAN STOL TERMINAL

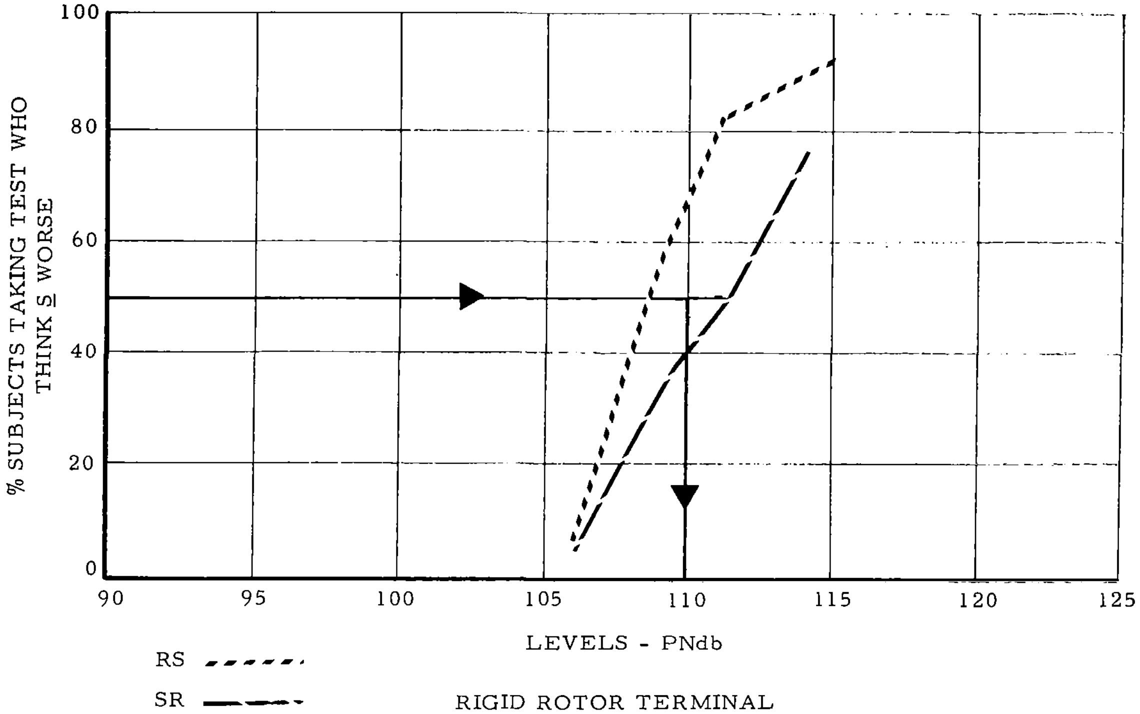


Appendix E: Part d.

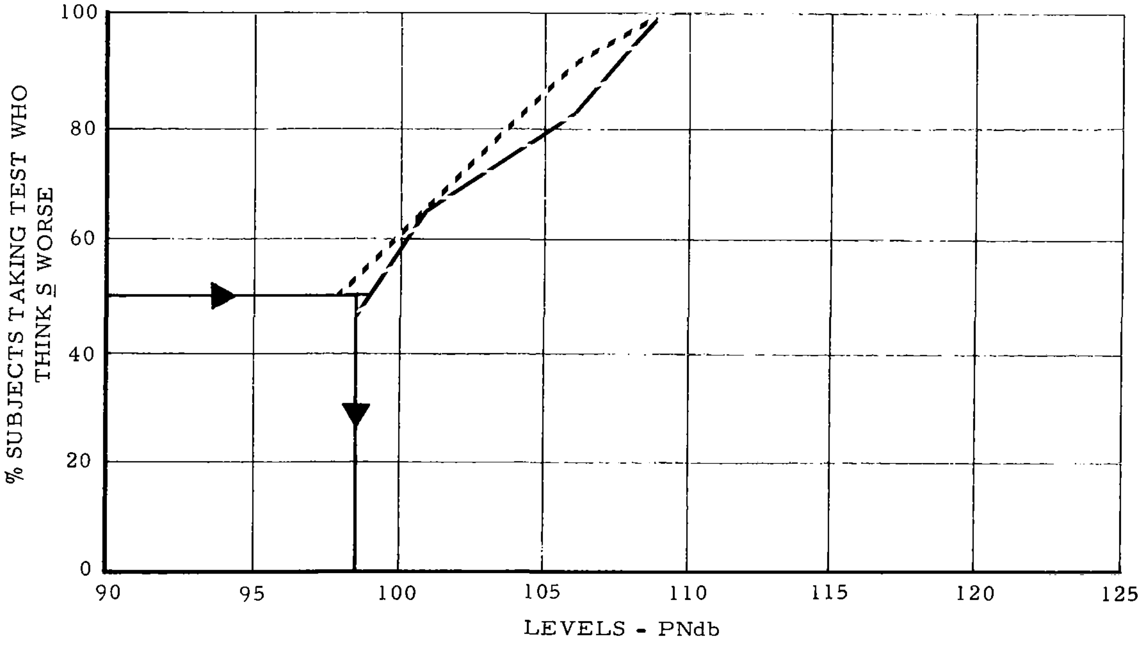
APPENDIX E

SUBJECTIVE TEST RESULTS
(OUTDOOR PNdb LEVELS)

RIGID ROTOR CRUISE



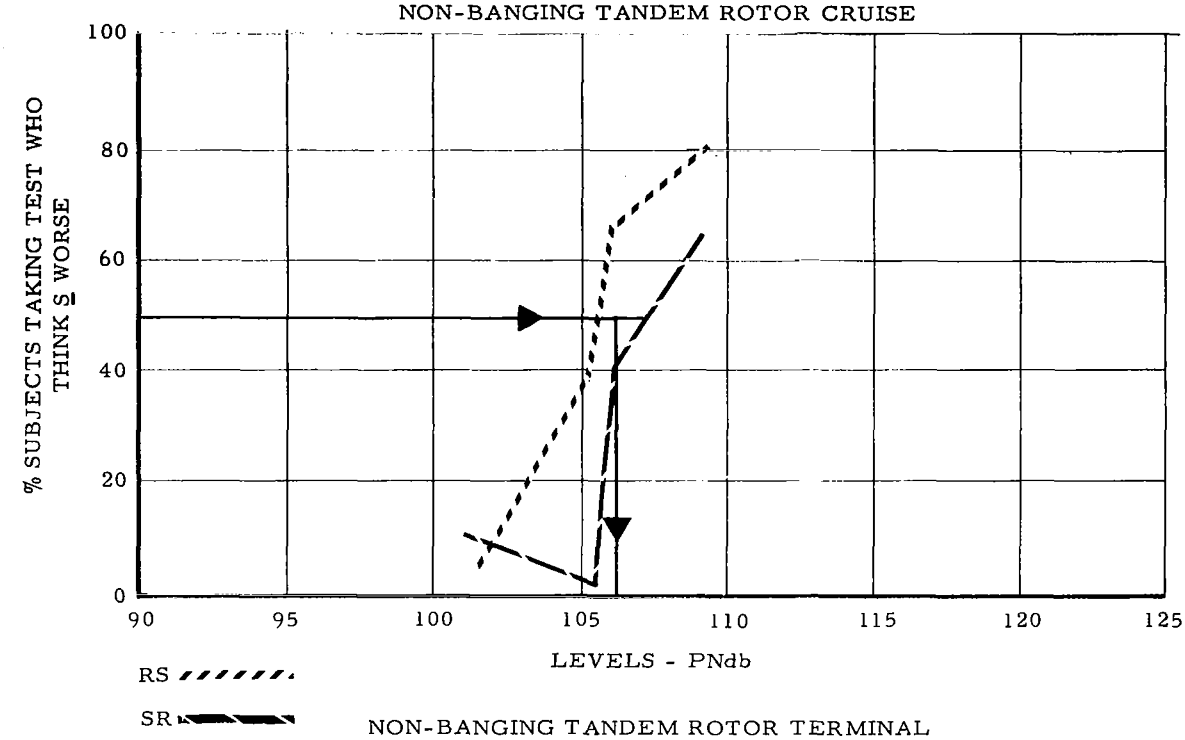
RIGID ROTOR TERMINAL

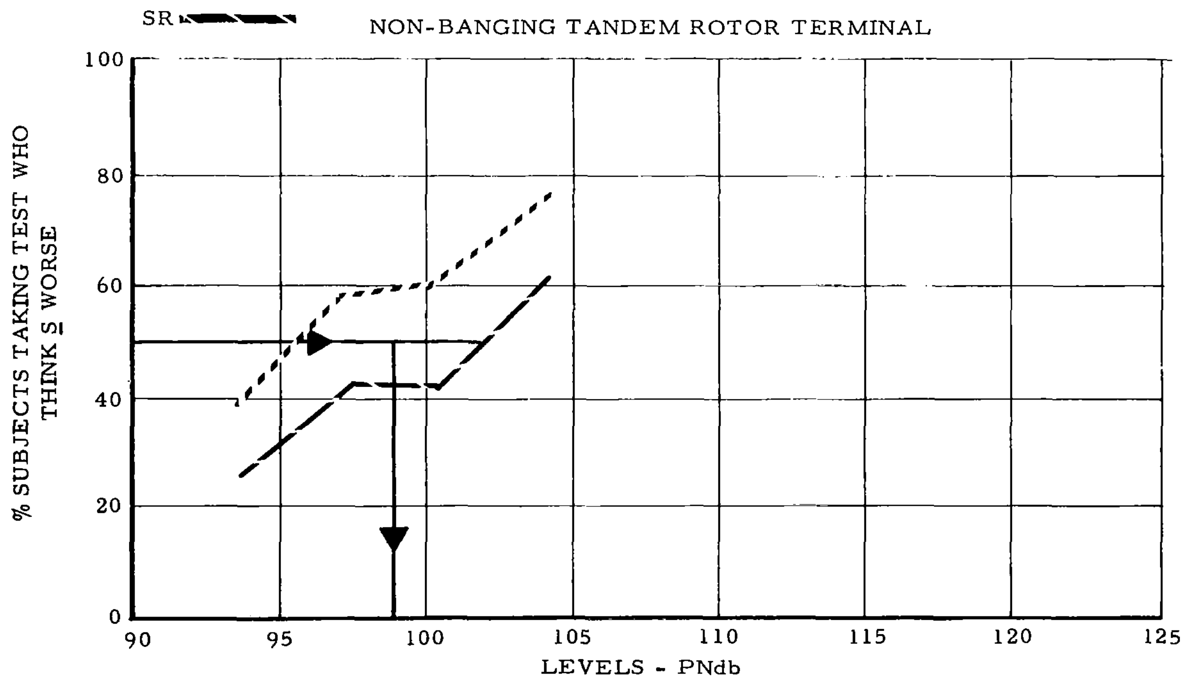


Appendix E: Part e.

APPENDIX E

SUBJECTIVE TEST RESULTS
(OUTDOOR PNdb LEVELS)





Appendix E: Part f.

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